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Energy requirements for water production, treatment, end use, reclamation, and disposal

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ABSTRACT

Energy is consumed at every stage of the cycle of water supply, treatment, use and disposal. The intensity of energy consumption (kW h/m^3) depends upon the specific technologies applied at each stage of the water cycle. For some technologies, the intensity may be relatively low, whereas the intensity of other technologies is substantially greater. This report surveys the available literature on energy intensity for water use in the municipal and agricultural sectors and separates the process into several stages. Water supply, water treatment, residential end use, wastewater treatment, and agriculture end use are considered. Representative values of the energy consumed per unit water are given for a broad range of processes. Water extraction and pumping from ground and surface sources is considered. The energy intensity of treatment required for different types of water source is found to vary widely between the extremes of relatively fresh surface waters, which use energy mainly in pumping, and seawater, which requires desalination. Energy usage for different methods of irrigation including pressurized as well as surface irrigation is studied. The energy intensity of residential end use is very high relative to other parts of the water supply cycle. Processes such as heating water, washing clothes and dishes, and cooking are briefly studied within the water end-use stage. Hot water usage is responsible for making end use the most energy intensive stage of the water cycle. Hot water use in different buildings is briefly reviewed. Wastewater treated with various processes is considered, and the energy intensity is found to be highest when advanced wastewater treatment methods are applied. Energy consumption in the agricultural sector, which is principally related to irrigation pumping, is generally of lower energy intensity than for the municipal treatment or end use.

Contents

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1. Introduction

Water is among the most basic and essential of human needs. Human beings not only consume water directly, but also use it in the production of food, for washing, sanitation, and for various industrial and domestic conveniences. The balance of water supply and demand is affected regionally by a broad range of factors including population growth, increasing urbanization, intergovernmental relations, political and policy choices, social factors, technological growth, and uncertainties of climate [1,2]. In addition to these issues, water consumption directly affects energy consumption. This energy consumption is the focus of the present paper.

The development of today's water treatment and distribution systems has been characterized by the US National Academy of Engineering as one of the greatest engineering achievements of the 20th century [3]. The infrastructure that provides water for agriculture, domestic consumption and sanitation requires extensive treatment and distribution systems that consume significant amounts of energy for pumping and purification. Further, various end uses of water, such as water heating, washing clothes and dishes, showering, and food preparation consume substantial amounts of energy. Water conservation is therefore directly linked to energy conservation. Alternative choices of water supply, treatment, end use and reuse can have very different implications for energy demand.

The ''water–energy nexus'' has garnered much attention recently. It includes both the energy consumption of water supply mentioned above and the water consumption of energy production processes [4–8]. Perrone et al. [5] proposed a ''water–energy nexus model'' to analyze the energy expended by a community to extract, treat, and discharge water as well as to analyze the amount of water used in the production of energy. In the present article, the consumption of energy for production, treatment, distribution, end-use, reclamation and disposal of wastewater is assessed taking into account processes, appliances and technologies.

1.1. Present scenario of water use in different sectors

Table 1 shows the water withdrawals, in cubic kilometers per year, by various sectors of use from various regions of the world. The contrasts are significant. Asia's water consumption is largely agrarian while North America and Europe withdraw more water for the industrial sector [9,10], which includes water withdrawn for thermal power plant cooling. From Table 1, industrial water use including power production accounts for 20% of total worldwide water use while use in the residential sector uses only 10% [9].

1.2. Background on water–energy life cycle

Wilkinson [8] outlined the major energy consuming components in the water life cycle. Since then, several studies have been

Table 1
Water withdrawals in different sectors [9].

Region	Available surface and ground water resources	Total water with drawn	Volume of water withdrawals (Gm^3/year)					Withdrawal as percent of renewable resource
			Agriculture		Industry		Domestic	
			Volume	Percent	Volume	Percent	Volume	
Africa	3,936	217	186	86	9	4	22	5.5
Asia	11,594	2378	1936	81	270	11	172	20.5
Latin America	13,477	252	178	71	26	10	47	1.9
Caribbean	93	13	9	69	1	8	3	14
North America	6,253	525	203	39	252	48	70	8.4
Oceania	1,703	26	18	73	3	12	5	1.5
Europe	6,603	418	132	32	223	53	63	6.3
World	43,659	3829	2663	70	784	20	382	8.8

performed on water-related energy consumption following a similar methodology. We will adopt that life cycle for the present work as well.

The water life cycle starts with production or extraction of water from natural sources such as ground water aquifers, lakes, rivers, and oceans. Fresh water from lakes and rivers normally requires treatment for the removal of micro-organisms and suspended solids such as sand or silt. In some cases, advanced treatment is needed to remove organic compounds, dissolved ions, or, in the case of ground water, absorbed gases. Many of these processes have a relatively low intensity of energy consumption. Seawater, being more saline than water drawn from most wells, rivers or other bodies, needs more stringent treatment measures to remove the very high concentrations of dissolved ions. Desalination is performed using thermal processes such as multi-stage flash (MSF) and multi-effect distillation (MED) or electrically driven processes such as reverse osmosis (RO) [11]. Energy consumption intensity for seawater desalination is substantially higher than for less saline waters. The energy consumption of water production and treatment is discussed in detail in Sections 2 and 3 below.

Treated water is used in different ways by various customers in the residential, commercial, industrial and agricultural sectors. For example, residential customers usually pump, heat, wash and cook, while agricultural consumers pump water to irrigate fields. The processes of pumping water, heating it, using it to wash clothes and utensils, or to process food consume widely varying amounts of energy per unit water [12,13]. These processes are examined more fully in Section 4.

Treated water may become polluted during its use in residential, industrial, and agricultural processes, and used water may require treatment before it is discharged or reused. The level of water pollution differs with sector and type of application, as do the treatment requirements. The energy consumption of wastewater treatment and reuse is discussed in Sections 5 and 6.

The importance of each stage in the water cycle is distinct and is also significantly affected by variations in the geographical location being served, water availability there, the local climate, the culture and customs of the area, and the economic status of the location. The present authors aim to provide a collective analysis of the major independent energy consuming processes within each stage in the cycle using datasets for separate locations. This approach is outlined in the water life cycle for residential or municipal sector as shown in Fig. 1, based on the structure laid out in previous studies [8,14].

The stages enumerated in Fig. 1 have been disaggregated to illustrate some of the energy consuming processes possible within each stage in water life cycle [15]. The energy consumed by each process is expressed in terms of kW h of electricity per cubic meter of water applied or served. Caution is to be exercised while dealing with different sources of energy and their application in water use processes. Several processes within Fig. 1 may consume energy from thermal sources under differing conditions of temperature and primary energy supply. This is particularly true of natural gas heating of water and of some steam driven desalination processes. In order to express energy in uniform units the authors have chosen equivalent electricity units of kW h. Therefore, a unit of thermal energy expressed in kW h may converted to equivalent electrical energy by assuming an appropriate efficiency of electrical generation from thermal power, e.g., assuming that 0.33 kW h of electrical energy is produced from 1 kW h of primary thermal energy under given conditions [16–19]. Contextually appropriate conversion efficiencies are applied in what follows.

2. Energy for water production

2.1. Ground water pumping

Deep well water (generally less than 300 m) is considered to be microbial free, but it can contain inorganic minerals such as iron, manganese, arsenic radionuclides as well as other chemicals originating from natural geological formations [20]; further, interactions with surface water can introduce agricultural run-off or microbial contamination. Extraction of water from underground aquifers primarily requires energy for pumping. Electrical energy (kW h) is expended when a unit volume (m^3) of water passes through a pump during its operation. An essentially linear relationship exists between the energy intensity value

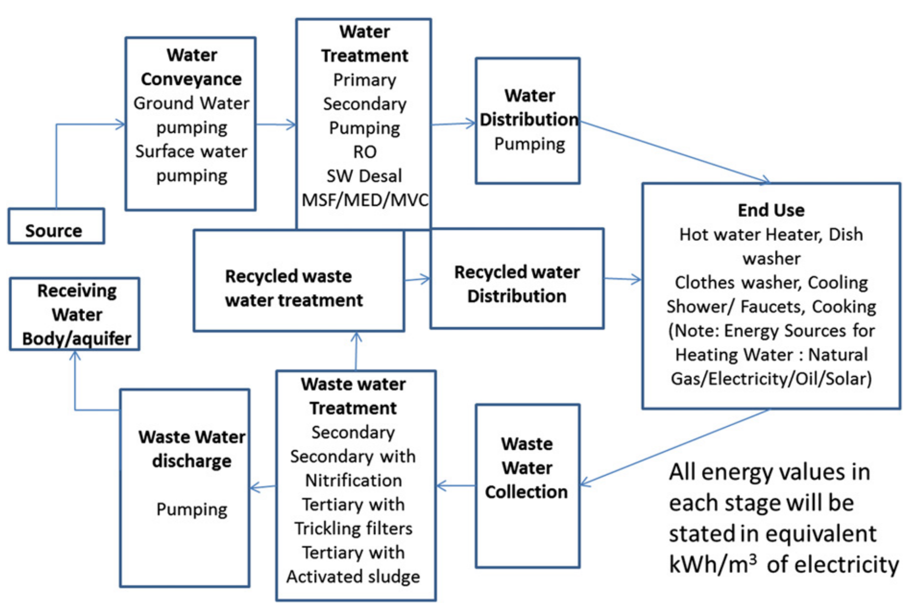

Fig. 1. Stages of the water life cycle through the municipal sector [8,15].

for ground water pumping and the depth from which it is pumped at a specific pressure [21]. This relationship is confirmed by the data shown in Fig. 2.

The amount of energy consumed in raising well water depends on the location of the water source relative to the location of discharge and also on the frictional resistance to flow [22]. It should be noted that the "lift" in Fig. 2 is not the depth of the well but the sum of the distance from the base of the pump to the static ground water level (water-bearing aquifer) and the ground water drawdown (long term cone-shaped depression in the aquifer ground water level that results from pumping). Designers placing more than one well at a location will set a distance of at least twice the aquifer thickness between two wells to prevent interference of the cones of depression [23]. The lift may change with water table variation depending upon climate or ground water recharge [24]. Lift dominates energy calculations in some water scarce areas of the world, such as northern China and arid regions of India [25,26]. As a numerical example, a system with a pumping lift of 46 m and requiring a discharge pressure of 4 bar would consume 0.367 kW h/m^3 of energy.

In any specific case, of course, a detailed assessment of the piping system, lift, pump characteristics, and well screens would give a more precise result [23]. Some of the general type of pumps used for drawing ground water are fixed speed, horizontal multi-stage centrifugal pumps, and submersible pumps (the latter especially for bore wells) [23]. The amount of energy consumed may depend on the efficiency of the pump, the pipeline line and diameter, pipe material roughness or friction factor, and the volumetric demand for water. Energy consumption, E_g (kW h), is therefore expressed as

$$E_g = f(l, Q, p, t, f_l) \tag{1}$$

where l is the distance through which the water is to be lifted, f_l is the friction loss along the distance l, Q is the required volume of water, p is the pressure requirement at the point of use and t is the time over which the water is pumped, assuming a constant head [22]. The engineering details of such calculations are beyond the scope of the present review.

Energy consumption by ground water pumps in California has been reported to range between 0.14 and 0.69 kW h/m^3 [27]. In Tulare Lake basin in California, a pumping energy of 0.14 kW h/m^3 is needed to lift water from 36 m below the surface [16]. Similarly, groundwater pumping expended 0.23 kW h/m^3 of energy to lift 61 m deep ground water in the San Joaquin River Basin [28]. The examples above would translate to a value close to specific ground water pumping energy use value of 0.004 kW h/m^3 m [16,29]. This figure is greater than gravitational head alone would require (that being simply water density times gravity, or 0.00272 kW h/m^3 m): Outlet pressure, pipe friction, pump efficiency, and lift affect this figure on a case-by-case basis.

Fig. 3 shows additional reported energy intensity for ground water pumping at several locations in California [30]. District locations in Fig. 3 are not in order from Northern to Southern California, although Anderson Cottonwood District lies in water abundant Northern California while San Luis Canal and Orange Cove are situated in water scarce Southern California. The figure does illustrate clearly how energy demand for ground water pumping rises with the depth from which ground water is pumped. From the figure, the energy intensity per unit lift for ground water pumping can be estimated as 0.006 kW h/m^3 m, somewhat higher than the previously stated value.

Extraction of water from wells in Ontario, Canada was reported to consume energy in the range 0.25–3.02 kW h/m^3, which is of similar magnitude, although well lifts are not given [31,32]. Maas [32] further quantified ground water well pumping energy consumption according to the flow rate: wells with a flow in the range 100–950 m^3/d consumed energy in the range 0.84–3.02 kW h/m^3 and wells with a flow in the range 1000–10,000 m^3/d consumed energy in the range 0.25–1.11 kW h/m^3.

2.2. Surface water pumping

Tunnels, aqueducts or pipelines, siphons, valves, and booster pumping stations are a part of most water supply systems. There are many large water supply systems around the world for which documentation is available. The energy consumption of these systems varies considerably depending upon the length of the system and the elevation changes involved. As an example of a very extensive supply network, about 2.4 kW h/m^3 of electricity is needed to pump water from Shasta Lake in Northern California through the Central Valley in 16 km long tunnels and over the Tehachapi mountain range (600 m lift) to the Metropolitan Water District, which provides water to Los Angeles, Orange, San Diego, Riverside, San Bernardino, and Ventura counties in Southern California [33–35]. The same amount of energy (2.4 kW h/m^3) was expended to lift water from Shoalhaven River in Australia to a height of 600 m before delivering it to Wingecarribee Dam near Sydney [36]. Similarly, Spain's national water project proposed in 2001 aims to transfer 860 GL/year of Ebro river water about 745 km to the south in Spain [37,38]. The predicted energy expense to supply water along the proposed Spanish Ebro river water diversion is depicted in Fig. 4. The values are comparable to that in the California system described previously.

Several authors have looked into the water conveyance energy expenditure for long distances. The conveyance of water from the Californian Colorado River Aqueduct as well as from San Francisco

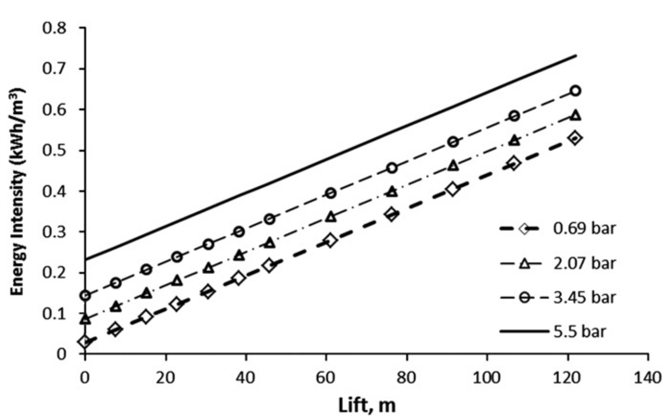

Fig. 2. Electricity required for pumping 1 m^3 of water as a function of lift with different discharge pressure requirements [24].

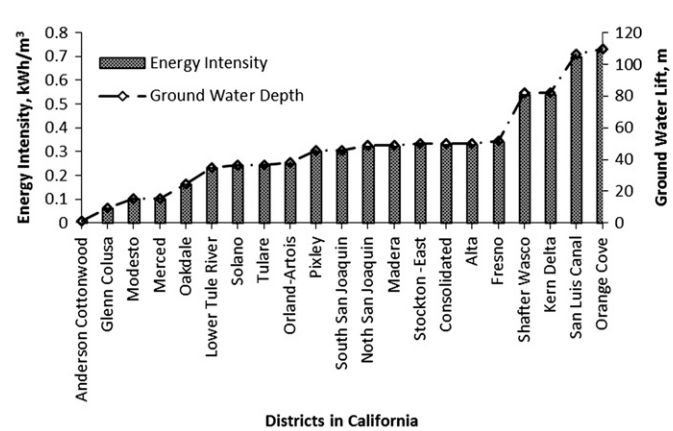

Fig. 3. Ground water pumping energy values across California [30].

Bay Delta to San Diego, CA consumed 1.6 kW h/m^3 and 2.6 kW h/m^3 energy, respectively [28]. Some other studies from California are tabulated in Table 2.

From the table, it is seen that the energy intensities of different surface water supply systems are location specific [39,40]. This specificity may be due to the grade in the pipeline systems, seepage or percolation properties of soil, solar radiation per unit area, and climatic behavior in a specific geographical region. Cheng [13] reported that energy consumption for unit volume of treated water varied due to distance as well as elevation of the area of service. For example, the Arizona Water Institute in 2009 reported a high energy intensity of 4.5 kW h/m^3 for drinking water conveyance to Tijuana, Mexico compared to other cities such as Durango, Guaymas, Monoclova, and Veracruz which required 0.56 kW h/m^3, 0.91 kW h/m^3, 0.60 kW h/m^3, and 0.4 kW h/m^3 energy to pump drinking water, respectively. The city of Tijuana in particular needed to extract water and pump it over mountains for its use [41]. It should be noted that Table 2 defines only the length of the transfer but does not provide detailed information on the mode of transfer. Most of the transfers discussed consist of a complex series of pipelines, pump and turbine stations, canals, and other water bodies interconnected to each other. Each mode of transfer has an independent contribution towards the total energy consumed. Therefore, a detailed assessment must consider the energy use of each mode of transfer separately.

For example, the energy consumption for surface pipe flow will be a function of grade, material or frictional resistance of the pipe or canal, as well as the geometry of the pipeline [20]. The energy consumption for pipe flows will be given by a function such as

$$E_{SPF} = f(l, Q, A, M, S, t) \tag{2}$$

where l is the length of the pipeline, A is the cross section area, M is a constant specific to the material (similar to Hazen–Williams coefficient for circular pipes), S is the slope of the pipeline, and t is the pipeline age [23]. Similarly, when considering water flow through any channel with a free surface subjected to atmospheric pressure, the energy consumption E_{SF} may be expressed as a function of the following variables,

$$E_{SF} = f(l, Q, R, k, M, S_c, f_l, T, P_r) \tag{3}$$

where l is the channel length with a constant or variable hydraulic perimeter R, M is a constant specific to the material, k is the permeability of the soil or the terrain bed, S_c is a parameter representing undulations on the bed or slope of the bed, f_l is the parameter defining the frictional and vegetative resistance, T is the evapotranspiration rate, and P_r is the rate of precipitation.

Fig. 5 compares the energy intensities of delivering 200 GL/year of water using pipeline, canal, tanker, and water bag distribution in the context of Australia [42,43]. The pipeline in Fig. 5 is proposed from the Willare Barrage on the Fitzroy River through a distance of 1900 km long with a rise of 700 m above the sea level before terminating at Westdale near Perth, Australia [43]. The 3700 km long canal also starts from the Willare Barrage on the Fitzroy River and terminates at Lexis north of Perth after which the water is treated and pumped into dams on Darling Scarp near Perth Australia. Here eight pumping stations with a cumulative lift of approximately 500 m with a 127 km rise is also to be utilized [43]. Fourteen shipping tankers of 500,000 dead weight tonnage to

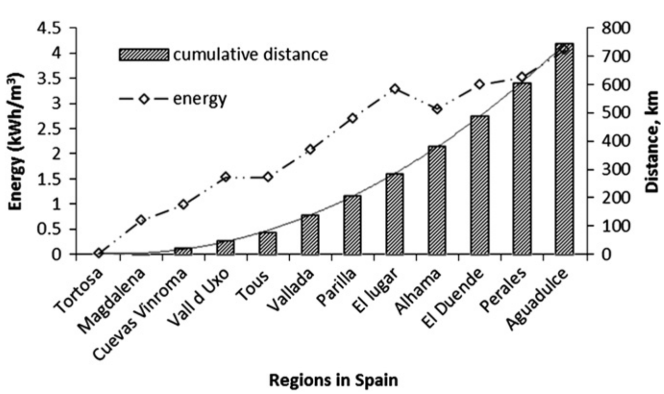

Fig. 4. The predicted specific energy consumption to supply surface water in southern Spain from the Ebro River [37].

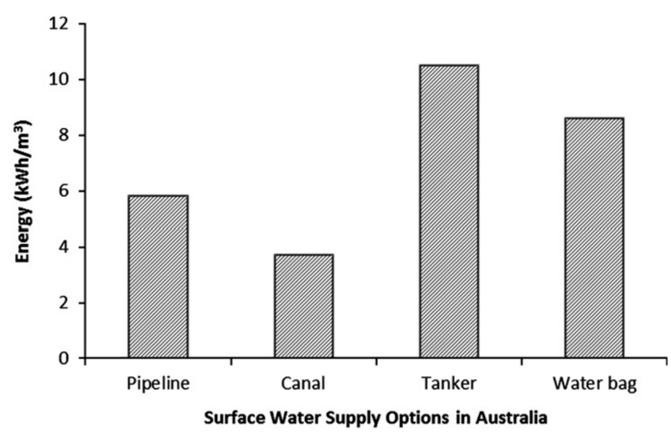

Fig. 5. Energy analysis of different surface water supply options proposed for Australia [42,43].

Table 2
The energy expended to supply surface water.

Name of the surface water supply	Length (km)	Energy consumed (kW h/m^3)	Energy use per unit distance (kW h/m^3 km)	Reference
California, USA				
West Branch Aqueduct, CA	502	2.07	0.004	[27]
Coastal Branch Aqueduct, CA	457	2.31	0.005	[34,36]
Transfer From Colorado River to Los Angeles, CA	389	1.6	0.004	[8]
Australia				
Water Pipe, Australia	450	3.3	0.007	[40,41]
[a]SSDP to [b]PIWSS	116	0.21	0.002	[41,42]
[c]PSDP to PIWSS	11.2	0.055	0.005	[41–43]
Spain				
Tortosa to Aguadulce	744	4.07	0.005	[37–38]

[a] Southern Seawater Desalination Plant, Perth.
[b] Perth Integrated water supply system.
[c] Perth Sea Water Desalination Plant.

deliver water were also proposed by GWA from Lake Kununurra on Ord river to Perth Australia, a distance of around 3000 km. Another option was towing a 0.5 GL water bag using a large tug boat as mentioned in Fig. 5 along the same shipping route [43].

3. Energy for water treatment

3.1. Treatment of raw water from ground and surface sources

Seven percent of worldwide electricity is consumed for the production and distribution of drinking water and for treating waste water [44]. Before supplying water to consumers, it must be treated to appropriate physical and chemical quality and must be free of protozoan, bacterial, and viral pathogens. Drinking water in particular must conform to water quality standards required by either the World Health Organization or governmental agencies such as the US Environmental Protection Agency. Generally, potable water at the point of supply should have a turbidity less than or equal to 5 NTU and zero fecal coliforms per 100 mL of water as per WHO guidelines, UK Regulations, European Commission directives, USEPA regulations, or and Bureau of Indian Standards guidelines [45,46].

3.1.1. Stages of ground and surface water treatment

Ground water pumped from subterranean aquifers may be discolored and may contain dissolved gases, inorganic and organic chemicals, or in some cases microorganisms. Basic disinfection of ground water might be carried out with the help of technologies such as chlorination or ozonation or ultraviolet irradiation. A ground water treatment plant may have a pumping system, a storage tank, a disinfection tank, and a booster distribution pump. Aeration to remove dissolved gases, oxidation and filtration to remove iron or manganese, or softening to remove calcium and magnesium ions may be applied as required. Fig. 6 plots the energy consumption in ground water treatment plants in the US.

Potable water is chlorinated to eliminate microbial contamination. Chlorination is usually accomplished by injection of chlorine gas into water or by the addition of salts such as calcium and sodium hypochlorite, containing around 70% chlorine, which form hypochlorite ions on contact with water [46]. Very meager energy consumption occurs during chlorination as seen in Fig. 6. Industrial development has introduced a host of anthropogenic materials that can pollute water and which may require advanced, energy intensive treatment processes. Energy associated with removal of these chemicals using processes such as aeration, ozone treatment, membrane treatment, etc., has not been included in Fig. 6.

Surface water extracted from rivers or lakes may be turbid and can contain impurities such as silt, algae, microorganisms, biological impurities, and possibly larger impurities such as plant materials, in addition to man-made organic or inorganic compounds (petrochemicals, pharmaceuticals, etc.). Surface water treatment stages are often ordered by the size of the impurities. These stages typically include mechanical screens, sedimentation or flocculation tanks, rapid mixing tanks, filtration processes, and finally disinfection tanks. When chemical contaminates are involved, additional processes may be introduced.

Energy consumption by various unit operations in surface water treatment plants are shown in Fig. 7. As expected, Fig. 7 shows that the raw water pumping intensity (e.g., from river to treatment plant), at 0.02–0.05 kW h/m^3, is minimal when compared to values seen previously for ground water pumping. Overall unit electricity consumption for US surface water treatment and supply is 0.079 kW h/m^3 [49]. This value is based on a unit electricity consumption of 0.073 kW h/m^3 for municipal surface water pumping with the balance expended for distribution pumping and primary treatment (e.g., softening, chlorination) of water prior to use [49]. DOE's Building Energy Data Book reports that 0.73 kW h/m^3 was consumed for pumping, treatment and distribution of water in Iowa, whereas Massachusetts consumed only 0.4 kW h/m^3 [50].

Sedimentation is a unit operation that helps in the removal of large discrete particles by settling under the action of gravity. Under quiescent conditions the particles will settle within the sedimentation tank. Settling velocities are proportional to the square of the particle diameter. In this operation, adequate settling time must be provided. The required time is calculated as a ratio of the volume of the tank V (m^3) to the flow rate Q (m^3/d). To promote better settling, Q should be minimal indicating a very low energy operation. Energy consumed during sedimentation is in the range 5×10^{-4} to 1×10^{-3} kW h/m^3 [48]. This energy is expended to maintain a very low velocity within the sedimentation tank (0.0025–0.0075 m/s) and to run variable speed agitators, with paddle speeds in the range 0.15–0.91 m/s [20].

Coagulation is necessary when the impurities are so small that settling velocities are negligible or when colloidal forces hold the particles in suspension. Coagulants are added to destabilize colloidal suspensions to promote agglomeration of particles. Common coagulants include such as aluminum sulfate (Alum) and ferrous sulfate and coagulant aids based on synthetic polymers. Anionic or cationic polymers as well as non-ionic polymers are added as flocculation aids at amounts on the order of 0.1–1 mg/L [20]. Energy consumption associated with utilization of polymers for coagulation is reported to range from 0.4 to 0.7 kW h/m^3 [51].

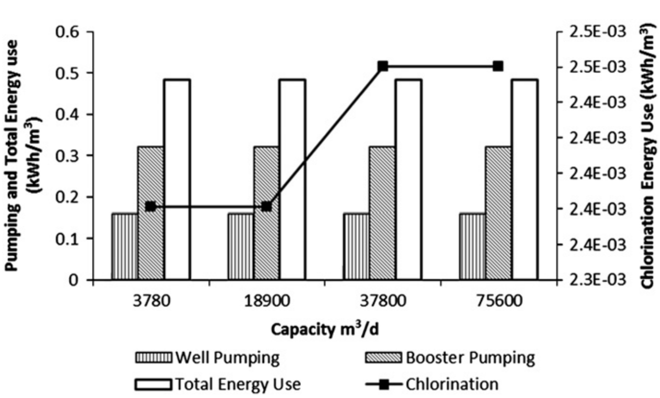

Fig. 6. Energy requirements for ground water treatment plants in USA [47].

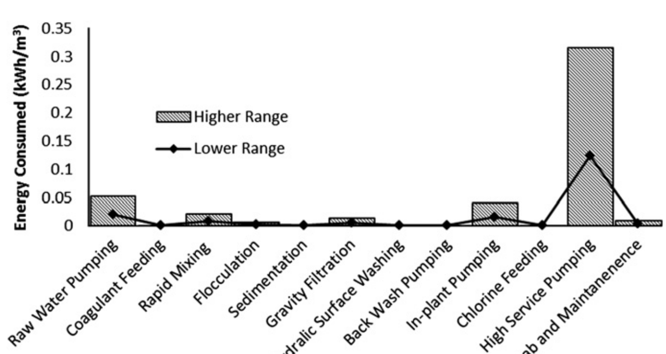

Fig. 7. Energy consumption of unit processes in surface water treatment plants in United States [48].

Table 3
Energy consumption of disinfection processes in a conventional surface water treatment plant.

Disinfection process	Energy range ($kW\,h/m^3$)	Reference
Surface water chlorination/de-chlorination	2×10^{-5}–5×10^{-4}	[12]
Ground water chlorination/de-chlorination	0.002	[12]
General UV irradiation process	0.01–0.05; 0.017–0.025	[53,54]
Ozone	0.03–0.1; 0.03–0.15	[12,53,55]
Hydranautics ultrafiltration membrane (HydraCAP 60)	0.025; 0.07–0.1	[53,55]
Microfiltration	0.18	[47]

A variety of chemicals may be used during water treatment, such as lime used for softening, carbon dioxide used for carbonation and pH adjustment, liquid oxygen for ozone production, polymers to enhance coagulation, ammonia for disinfection, sodium hexametaphosphate to stop softening as well as to prevent calcium precipitation, sodium hypochlorite to disinfect water, sodium silicofluoride for addition of fluorides for dental protection, and sodium hydroxide for increasing pH of water [51]. Dispersion of chemicals is performed using mechanized impellers, static mixing elements, or nozzle injector-driven diaphragm pumps [20]. Energy expended for chemical dispersion using rapid mixing shown in Fig. 7 is in the range 0.008–0.022 kW h/m^3 [48]. High rate clarification is another process in which micro-sand (60–120 μm) is used to enhance sedimentation and flocculation process [20]. This process is helpful for treating water infected with algal blooms, water with fluctuating quality, or water affected by natural organic matter or carbon. In this process, flocculation aiding polymers as well as micro-sand is added to promote the formation of agglomerated particles. The detention time in the settling tank is around 6 min. The energy consumption of surface water treatment plants with high rate clarification reported at the city of Lincolnton, North Carolina (34000 m^3/d) to be about 0.009 kW h/m^3 and at Tampa Bay, Florida (250,000 m^3/d) to be 0.012 kW h/m^3 [48].

Another methodology for removal of algal blooms and dissolved gaseous impurities which were not removed by coagulation or settling is dissolved air flotation [48]. Energy is consumed for supersaturating a pressurized stream of clarified effluent with air. This energy is required to overcome the pressure drop across the nozzles which release air into the effluent stream. Air bubbles through the water, aiding flocculation and helping removal of dissolved gases. Energy consumption during this process is in the range 9.5×10^{-3}–35.5×10^{-3} kW h/m^3 [48].

Filtration is a polishing step that helps in removing impurities remaining after the settling and coagulation stages. Some flocs are carried over to accomplish the removal of minute microbial impurities that would otherwise escape through the porous granular media filter [23]. Filters classified according to materials consist of deep bed anthracite filters, coal–sand dual media filters, mixed media filters, activated carbon filters, and diatomaceous earth filters. Direct filtration is employed when the turbidity levels are below 20 NTU. From Fig. 7, the energy consumed by these gravity filters is found to be in the range of 0.005–0.014 kW h/m^3.

After the removal of most of the solid impurities, even if the physical and chemical characteristics of water are acceptable, it is still not fit for drinking until it is free from bacteria and other microbial pathogens. A selection of common water disinfection technologies and their energy consumption are tabulated in Table 3. Chlorination of surface water is found to consume energy similar to ground water chlorination shown in Fig. 6. Another disinfection process is ozonation, which does also oxidize taste and odor causing compounds present in water [52]. Ozone is produced as pure oxygen is fed between two electrodes. These electrodes are separated by a dielectric material across which high voltage is maintained. This ozone production consumes approximately 0.2 kW h/m^3 [48,52]. Ozone production is expensive when compared to chlorine.

Table 4
Conventional water treatment energy consumption ranges in several countries.

Country	Energy consumption ranges ($kW\,h/m^3$)	Reference
Australia	0.01–0.2	[57]
Taiwan	0.16–0.25	[13]
USA	0.184–0.47	[48]
Canada	0.38–1.44	[32]
Spain	0.11–1.5	[38]
New Zealand	0.15–0.44	[58]

Table 3 also includes pressure-driven membrane processes such as ultrafiltration, which filter impurities on the basis of their size. These processes may be advantageous over conventional disinfection since they can filter bacteria as well as viruses, they do not produce disinfection by-products, they produce non-turbid permeate, and they are compact and can be easily automated [56].

Table 4 reviews reported ranges of energy expenditure for water treatment in several countries. Spain is seen to have highest upper limit energy consumption for water treatment. Spain uses reverse osmosis desalination to treat some water [38], and, as will be discussed in the next section, these processes can be very energy intensive. Canada is also found to have a high energy intensity due to the use of high energy membrane processes such as ultrafiltration in use and smaller plant sizes ($<$500,000 m^3/d) [31].

3.2. Water treatment for higher purity requirements and desalination

In arid and water scarce areas, desalination technologies have become a viable source of water. Desalination is employed to remove high concentrations of minerals and salts from seawater, as well as in treatment or recycling of brackish water. Two major classes of desalting processes are thermal and membrane desalination. Thermal separation processes include multistage flash distillation (MSF), multiple effect distillation (MED) and mechanical vapor compression. Membrane processes rely upon the application of pressure or electric fields to separate ions from water. While the 60% of the world's desalination capacity is reverse osmosis (RO), thermal technologies still represent about 80% of worldwide capacity for seawater desalination [59]. The latter is dominated by a number of large MSF and MED plants in the Arabian Gulf. A detailed outline of energy intensities for desalination processes is given in Table 5.

The minimum energy required to desalinate water is proportional to the salinity of the raw water, but the energy required in practice also depends upon the technology employed. The energy consumed in membrane processes such as reverse osmosis, nanofiltration, and electrodialysis varies with the salinity of the water, whereas the energy required in thermal [distillation] processes is independent of the salinity of the source water. The minimum energy consumption in reverse osmosis membrane processes is determined by the need to pressurize the inlet water stream above its corresponding osmotic pressure [60,61].

In general, brackish waters (1500–15,000 ppm of total dissolved solids or TDS) require less energy to desalinate than seawater (15,000–50,000 TDS); and reverse osmosis is generally more energy efficient than thermal processes [62,63]. RO desalination of brackish water with 500 ppm, 1000 ppm, and 4000 ppm TDS consumes roughly 0.66, 0.79 and 1.59 kW h/m^3, respectively,

Table 5
Energy consumption for desalination processes.

Energy consumption values in kW h/m^3									
Timeline	**Thermal processes**					**Mechanical process**			
	Multi stage flash		Multiple effect distillation		Vapor compression	Sea water RO	Brackish RO	Electro-dialysis	References
	Electrical energy for pumping	Thermal energy (equivalent electrical energy)	Electrical energy for pumping	Thermal energy (equivalent electrical energy)	Electrical energy	Electrical energy	Electrical energy	Electrical energy	
2005	3.0–5.0		1.0–2.0		8.0–12.0	3.0–6.0, 6.8		0.8–1.5, 1.7	[67,68]
2005						2.0–4.0, 4.2			[37,69]
2008	3.0–5.0		1.5–2.5		8.0–15.0	2.5–7.0			[28]
2010	2.5–4.0		1.2–1.8		8.0–16.0	5.0–6.0			[66]
2010	3.2–3.7	(9.8–6.8)	2.5–2.9	(6.6–4.5)	8.0–17.0	3.3–8.5	1.0–2.5		[39]
2010	4.0–5.0	78 (10–20)	1.0–1.5	69 (3)		3.5–4.5, 3.0–4.0	1.0–2.0		[38,70]

while seawater reverse osmosis consumes energy in the range of 2.5–7 kW h/m^3 [28,64,65]. Thermal processes are almost universally driven by low temperature steam extracted from an adjacent power plant, rather than electricity as for reverse osmosis; and as a result it is important to carefully distinguish the type of energy being consumed when comparing thermal to electrically driven desalination processes. The electrical equivalents of thermal energy input in Table 4 are based upon the amount of electrical generation capacity that is lost when steam is extracted from a power cycle in order to drive MED or MSF desalination. That electrical energy in turn depends upon the steam pressure and temperature at the location of extraction.

As an example of integrated water-power plants, the Hebei Guohua Candong 6.4 GW coal-fired power plant in China has a low temperature multi-effect desalination system with equivalent electrical energy consumption of 6.282 kW h/m^3 [66]; and Shuqaiq II in Saudi Arabia is a 216,000 m^3/d water and 850 MW power production plant which has a two-pass RO treatment system consuming 4.4 kW h/m^3 [59].

In comparison to the treatment of fresh ground and surface water, desalting is much more energy intensive. But new innovations in desalting technologies aim to reduce this energy gap. Energy recovery devices are now widely used to recover the energy loss in the high pressure brine reject stream. Centrifugal energy conversion devices include turbines, positive displacement devices, rotary pressure exchangers, and have efficiencies that can exceed 95%. Similarly, Penate et al. [71] reported that adding an RO Kinetic® pressure exchanger energy saving system to a 2000 m^3/d seawater RO reduced its energy consumption to 2.1 kW h/m^3 from 3.5 to 4 kW h/m^3; in another report, a two-pass seawater reverse osmosis system achieved 45% energy recovery, consuming 3.3 kW h/m^3 [61].

McGinnis and Elimelech [72] proposed a single column low temperature forward osmosis seawater desalination process which consumed 0.85 kW h to produce a cubic meter of salt free water at a very low permeate flux. The driving force of the forward osmosis process is the osmotic pressure of the draw solution. Recently Sarkar and Sengupta [73] proposed a new technology which altered the feed water chemistry with a reversible anion exchange process before it was filtered using a nanofiltration process. This hybrid ion-exchange nanofiltration methodology was able to produce 1 m^3 of permeate at the expense of 0.89 kW h of electricity. Some reports of new technologies come so close to the second law limitation on work of separation that they should be regarded as promising but preliminary from the standpoint of deployable technology. Further renewable sources of energy are being considered for driving desalination processes, thus conserving non-renewable sources of energy. Narayan et al. [74] surveyed solar-driven humidification and dehumidification desalination technologies available as of 2010, and found that these technologies consumed *thermal* energy of as little as 140 kW h per unit cubic meter of water produced using very simple technology. The use of solar photo-voltaics (PV) along with RO technologies have generated much interest [75]. The specific electrical energy intensity of these hybrid systems depends upon the salinity of the feedwater and upon whether or not energy recovery is being used; in general the energy intensity is similar to that already reported for reverse osmosis systems. Apart from PV, wind powered systems have attracted interest. A wind powered mechanical vapor compression desalting system in Borkum Island, Germany produced water at a rate 0.3–2.0 m^3/h with an energy intensity of 16–20 kW h per cubic meter of water produced [75]. The other renewable form of energy can be derived from ocean waves. One of the first desalination systems (10 m^3/d) run with wave power was installed in Kerala, India and reportedly consumed 1.85 kW h/m^3 with a 25–35% recovery [76]. For renewably driven systems, however, the major consideration will be the capital cost of the energy generation technology, for example, expenditures for PV panels or solar thermal collectors. Often, the water produced by renewably powered systems is relatively expensive as a result of these investments.

Desalination is energy intensive but when overall costs, life-cycle energy expenditures, and environmental impacts are taken into account, it may remain advantageous relative to alternatives such as long distance water transfers. For example, the proposed transport of water across China (South to North Water Diversion Project) is projected to have very high energy consumption related to the creation of hydraulic infrastructure to have higher unit water cost than desalination projects [4,77]. Similarly, other processes with the stages of the water–energy cycle may consume substantially more electricity per unit volume of water applied or served.

3.3. Booster pumping energy consumption

It can be inferred from Figs. 6 and 7 that booster pumping is an important element of water treatment plants in the United States. Energy consumed for pumping water into the pressurized distribution systems amounts to about 85% of the total energy consumed by conventional water treatment plants [12]. The pumping of water into the distribution system is less energy intensive per unit water with an increase in the volume of water pumped, as seen in Fig. 8, which illustrates the energy consumption in pumping treated water to cities in Switzerland.

Energy consumption in pumping water to a residential distribution system in Taiwan ranged from 0.1 to 0.26 kW h/m^3 [13]. Booster pumps performing the same process in California

consumed energy in the range 0.015–0.41 kW h/m^3. This range of energy consumption is very low as compared to the energy ranges illustrated in Fig. 8 for Switzerland. This may be due to the difference in the pumping loads, the number of consumers, elevation changes, and the pressure requirements at end use. Municipal water pumping in Ontario, Canada consumed electrical energy in the range of 0.68–1.1 kW h/m^3 [31]. Zerah [79] reported that the total population with access to drinking water may be considered a measure of water supply. Geography also plays a decisive role in influencing the values of energy expended on water supply [5,80]. For example, Loudoun, a small city in a mountainous valley in Virginia, has a population of 39,000 people but consumes 2.27 kW h/m^3 for its water supply, while Alexandria in the flatter northern part of Virginia with a population of 900,000 consumes 0.5 kW h/m^3 [80]. China, with a very high population density, produced and supplied water in 1997 with an average energy consumption of 0.079 kW h/m^3 while this energy figure rose to 0.093 kW h/m^3 in 2004 [4]. Water consumption in the Chinese industrial sector increased from 112 Gm^3 in 1997 to 122 Gm^3 in 2004. Similarly residential consumption of water in China jumped from 52.2 Gm^3 to 65.1 Gm^3 [4]. This suggests that rapid urbanization and increasing end use increases energy demand for water extraction and supply.

4. Energy consumption for water end use

Water is a very essential commodity in the residential sector. The World Health Organization defines the average water requirement for human survival to be about 0.0025 m^3 per capita per day [81]. Residential areas in North America and Japan use 0.35 m^3 of water use per capita per day [82]. Similarly Europe consumes approximately 0.2 m^3 per capita per day. In contrast, only 0.01–0.02 m^3 per capita per day is consumed by residences in Sub-Saharan Africa [82]. Similarly households in African countries like Kenya used 0.045 m^3 per capita per day, Uganda used 0.047 m^3 per capita per day and Tanzania consumed 0.07 m^3 per capita per day [83]. Table 6 tabulates the per capita water use in countries of Asia and South America. Worldwide, residential water use has seen an increase over the last two decades (Fig. 9).

Water use tends to decrease with an increase in distance to the water source. For example, in the case of a developing country, if the public standpipe is closer than 1 km water use is approximately 0.02 m^3/person d, but if public stand pipe is beyond 1 km in distance the water use diminishes to less than 0.01 m^3/person d [81]. Household water use also changes with climate. For example, the water use in a household in a humid developing nation was reported to be 0.02–0.04 m^3/capita d and in a dry region it was reported to be about 0.06–0.08 m^3/capita d [81].

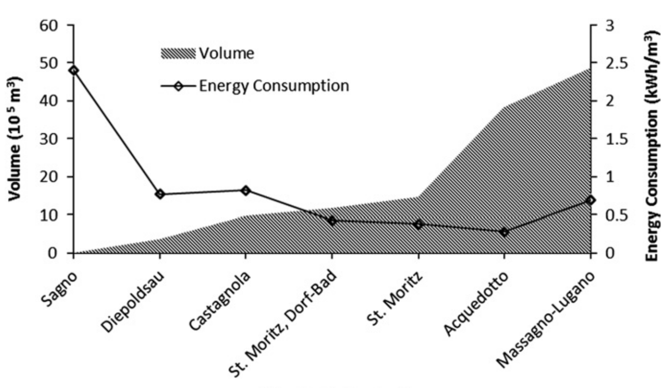

Fig. 8. The energy intensity of treated water supply for residential end use [78].

Table 6
Residential water use in Asia and South America [80].

Cities in Asia	Urban household water use (m^3/capita day)	Cities in South America	Urban household water use (m^3/capita day)
Kathmandu	0.09	Santa Catarina	0.14
Dhaka	0.09	Minas	0.15
Beijing	0.09	Bogota	0.16
Mandalay	0.11	Santiago	0.20
Hong Kong	0.11	Costa Rica	0.20
Suva	0.13	Brasilia	0.21
Shanghai	0.14	Sao Paulo	0.23
Colombo	0.16		
Singapore	0.18		
Kuala Lumpur	0.20		
Manila	0.20		
Seoul	0.21		
Delhi	0.21		

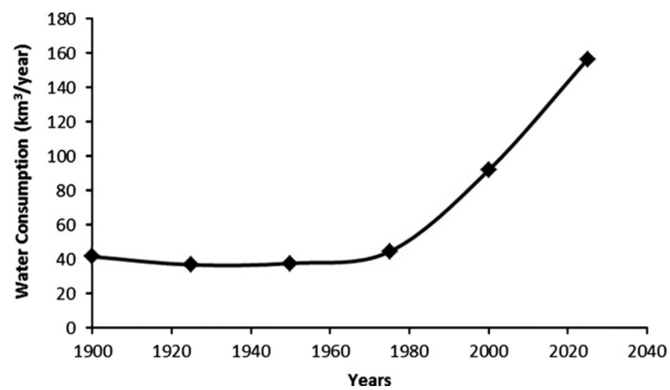

Fig. 9. Residential water consumption in the world [84].

In the residential sector, various appliances and processes are water intensive. Table 7 lists a number of processes and the estimated daily water consumption involved in the US. Faucets, clothes washers, showers, and toilets are the major water consuming processes.

End use energy intensity is very high relative to most processes discussed so far, and human behavior has a very substantial role in setting water related energy consumption. Janda [86] observed that building occupants are the real consumers of energy and not the building itself. Therefore, the behavior of the occupants of a building may be more important than the specific features of a particular building. The decisions of the occupants may vary with climatic change, washing habits, metering of water, the number of consumers in the house, and also on the design of the piping and the number of faucets in a specific residence [46].

4.1. Residential sector: Human behavioral aspects

Energy consumption in residential sector is influenced by the behavior of the occupants and their water demand [87]. Bathing is the most hot water intensive activity within a residential home [88]. Seven houses surveyed by Kempton [88] exhibited a wide variability in hot water usage range with a low of 0.089 m^3/d to the high of more than 0.5 m^3/d. The consumption of energy for water heating was measured by Kempton to be about 1.8–4.7 kW h/d for a person. In addition, the residential sector will always have randomly distributed water consumption events [89]. Some behavioral aspects and actions of hot water consumers have been identified to characterize this randomness, such as intermittent use: After any hot water use, the remaining hot water

Table 7
Residential water use distribution by process in the US [78,85].

Processes	Percentage of total daily use	Water use (m^3/capita)
Faucets	0.239	0.041
Clothes Washer	0.221	0.038
Showers	0.195	0.033
Toilets	0.180	0.031
Leaks	0.088	0.015
Baths	0.027	0.005
Dishwashers	0.015	0.003
Other domestic Uses	0.034	0.006

in the pipe will cool off gradually, wasting a significant amount of energy [13]. Kempton also predicted that non-point-of-use consumers underestimated their energy usage while consumer in countries with point-of-use water heaters may overestimate the energy consumed. Individual behavior, life style, psychological, cultural and social factors and gender preferences are some other factors that may influence end use energy consumption in a residential sector [90]. The overall contribution of water heating in housings is large. In Queensland, Australia heating and cooling home spaces accounts for 39% of residential energy use while hot water heating alone accounts for 27% [91]. In the USA, 14–25% of the energy supplied to residences heats water.

The European Commission in 2010 noted that human behavior can have a significant impact on sustainable water management at homes. The average showering time for an individual in the UK and Australia was 7.2 min [92,93]. Walker and Higgins [92] reported that people below the age of 18 spent more time under showers than the 18–34 age group; there was not much change in showering time with respect to gender [92]. Showering, using faucets, and bathing in bathtubs on average consumed 5.4 kW h/m^3 of electricity in Arizona [94]; this figure is averaged over all types of water use, both cold and hot. If heating energy is excluded (so that pumping alone is considered), on average, the energy consumed for bathing was reported to be 0.04 kW h/m^3, for showering it was also 0.04 kW h/m^3, and for using a faucet it was also 0.04 kW h/m^3 [95].

Similarly, Walker and Higgins [92] reported that people in United Kingdom often kept running their taps while they brushed their teeth. The results from their studies are plotted in Fig. 10. Tap running time can be used as evidence of unnecessary water consumption, and potentially as a flag for added energy consumption.

Behavior and cultural aspects also have a great influence on the water consuming products preferred in the local in the market. People in Japan favor small appliances [96]. People do not buy large drum shaped washing machines, which are larger than the preferred vortex impeller clothes washer [96]. An NREL study reported that flow rates are normally distributed for all end uses [97]. But it is not the case for events like showering, flushing the toilets, dish washing or washing clothes. NREL also reported a lognormal distribution for shower event duration as well as dishwasher operating time.

Several strategies may be used to manage human behavior and help prevent unnecessary expenditures of energy for water end use. These include government regulations, incentives for water conservation, technological features, and influences due to social interactions [98–101].

4.2. Water cooling and heating

Water is usually heated or cooled before consumption at end use. Equivalent electrical energy consumed for cooling water from a room temperature of 20 °C to around 3 °C is about 18.2 kW h/m^3 [53]. Electricity consumption of refrigerators during recent decades is illustrated in Fig. 11 [102]. The value of electricity

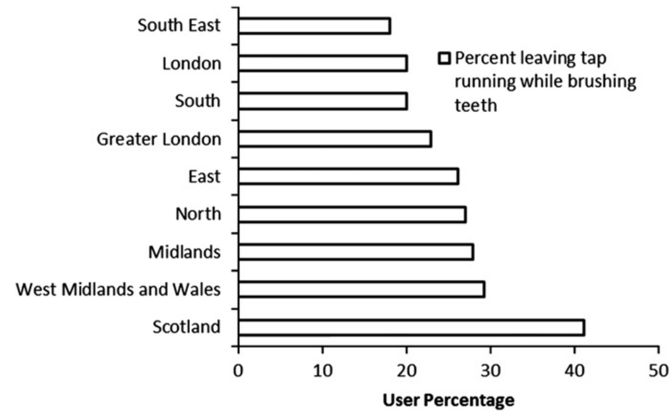

Fig. 10. Percentage of instance in which the tap was running during tooth brushing in the UK [92].

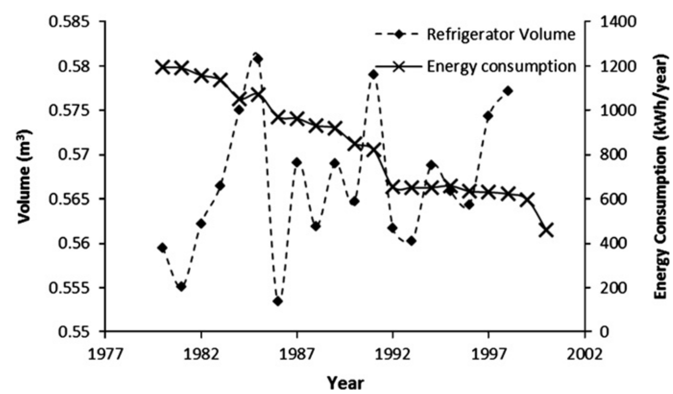

Fig. 11. Average annual electricity consumption for refrigerators and average volume of refrigerators available in the US market by year [102].

consumption in the year 2000 was 469 kW h/year. Gleick and Cooley [53] reported that average refrigerator electricity consumption was about 450 kW h/year per refrigerator in the US. Average energy consumption of refrigerators available in India is approximately 359 kW h/year per refrigerator [103].

In the residential sector, hot water is used in dish washing and clothes washing. The other uses of hot water are for showering, cooking, and sometimes boiling water to disinfect or to cook. There is a wide diversity in commercial brands of water heating options available and hence it becomes difficult to set any criteria for use when doing life cycle energy analysis in residences worldwide. The energy efficiency of some water heaters in the US market are shown in Fig. 12.

The energy factor for a water heater is calculated by dividing the energy content of the heated water by the energy required to heat the water [105]; high efficiency in water heating is reflected by a high energy factor. Heat pump water heaters, which capture heat from the air and transfer it to water, have a higher energy factor than other types of water heaters [104]. Electrical water heaters (energy factor of 0.93) were more efficient when compared with natural gas heaters (energy factor of 0.63), primarily because gas water heaters lose some of their energy up the exhaust vent [104]. However, electricity itself must be produced from another fuel, so that primary energy consumption for electric heaters is in fact higher than for gas heaters. The equivalent electrical energy consumed by natural gas water heaters was calculated to be 35 kW h/m^3 (0.035 kW h/L), which is less than electric water heaters at 73 kW h/m^3 including losses [32]. In

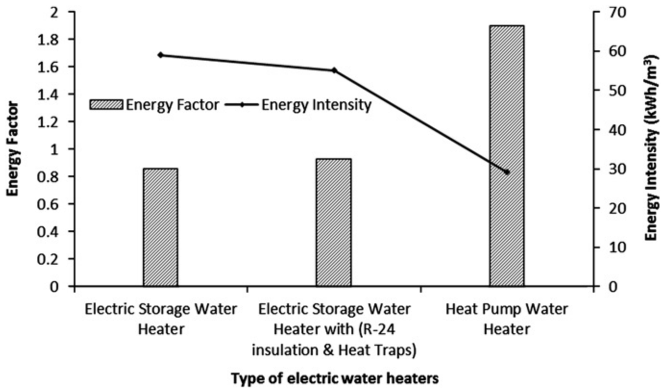

Fig. 12. Comparison between the energy consumption and efficiency of some types of water heaters in US market [104].

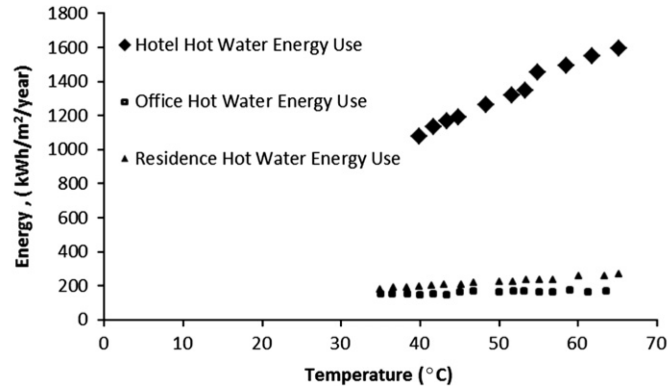

Fig. 14. Linear relationship between temperature of water and energy expended to heat water in different building types in Senegal [113].

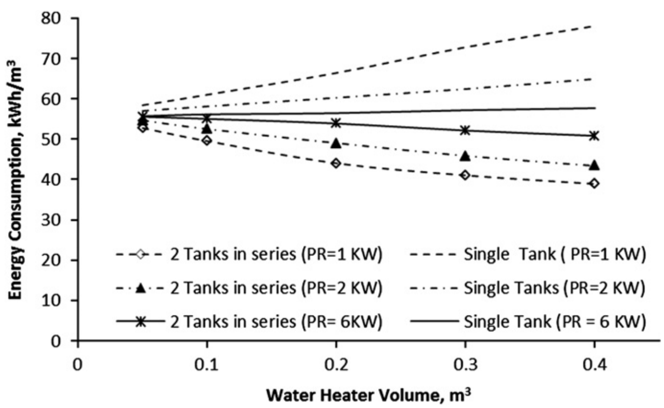

Fig. 13. Energy consumed (per cubic meter of hot water) by single tank and series tank (two tanks) water heaters [106]. PR=power rating.

general, the energy required for heating water depends on the initial (cold) and final (hot) temperatures of water.

For single tank storage water heaters, the energy consumption increases with size (Fig. 13). Two tank storage water heaters have two adjoining tanks in series one after the other. Energy consumption decreases with size for a series tank water heater irrespective of power rating. For single tank storage water heaters, energy consumption increases with an increase in heater power rating. A decrease in power consumption with decreasing power rating of two tank storage water heater is observed from Fig. 13 [106]. These designs were based on having 75% of the storage in the first tank with 75% of the heating power in the second tank.

4.2.1. *Energy consumption of buildings related to hot water use*

Residential water heating consumes about 3.5% and 4% of the total energy demand of US and Canada, respectively [107,108]. Water in US and Canada are heated using either electricity or natural gas [88,109]. The energy cost of water heated with natural gas is predictably lower than when using electricity. US consumers spend US$200 or US$400 for natural gas water heating and electric water heating per year, respectively while Canada spends US$400 or US$700, respectively, on natural gas water heating and electric water heating per year [108,110].

The variables of interest in water heater energy consumption are the volume of water, the temperature at inlet and exit of the heater, amount of electricity or gas expended for heating the volume of water, and the required water temperature at the point of use [88]. While energy consumption in heating water is very high, this consumption differs from building to building depending on its purpose and usage. In comparing a household, a hotel at a prominent location, and a hospital, hot water usage depends on the relative frequency of use by the occupants and the density of occupants within the building [88,111,112].

Ndoye and Sarr [113] reported that irrespective of building type energy varies linearly with water temperature while energy has a parabolic relationship with flow rate of water. The linear relationship between temperature of water and energy required to heat the water within a unit area of service is confirmed from Fig. 14. Similar studies reported that average specific heating energy consumption for domestic hot water heating in Finland is 53 kW h/m^2 year [114].

Ndoye and Sarr [113] also postulated that the difference in energy consumption among different buildings varied relative to their needs. Hospitals and hotels have fairly constant demand for hot water throughout the year. Hot water use energy consumption values of hospitals in USA were 5.27–7.77 kW h per hospital bed per day and for Europe it was 4.16–6.94 kW h per hospital bed per day [111].

Similar studies on water heating were performed in Northern California by the Pacific Gas and Electric Company [115]. A summary of those investigations is presented in Fig. 15. The demand for hot water increases varies with the type of business facility. Restaurants and hospitals consumed a high amount of electricity to heat water for its customers, while schools and retail businesses consumed comparatively less. Hospitals, for example, provide comfort to patients and expend hot water in clinical processes; restaurants expend hot water for processing food and for washing. In this figure, the relative amounts of electric or gas heating reflect the systems installed in the areas facilities studied, rather than specific features of the heating technologies; one may conclude that hospitals and hotels generally favor gas water heaters.

Related studies on hot water use in buildings were performed by Arpke and Hutzler [12] (Table 8). The results in Table 8 illustrate that residential hot water energy consumption was more than commercial office building hot water use, in agreement with the studies from Senegal previously mentioned. Comparative values for residences are given by Cheng [13], who reported that Taiwanese residences consumed 5.55 kW h/m^3 of all water used (both heated and unheated). This value included energy expended for warm water use in showering of 25.6 kW h/m^3. These studies confirm that the amount of energy used to heat water is determined by the type of business in the commercial sector, number density of consumers, and type of fuel used. Because water from a hot water heater is usually blended with cold water to produce a

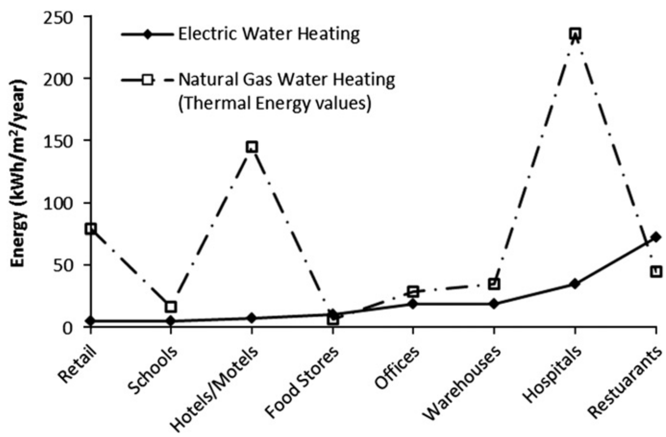

Fig. 15. Electrical and natural gas water heating energy intensities for commercial buildings in Northern California, USA [115].

Table 8
Energy intensities of using hot water in different buildings [12].

Building type	Equivalent electrical energy intensity (kW h/m^3)	
	Natural gas	Electricity
Apartment	11.9	28.8
Dorm	9.3	22
Motel	8.9	22
Office building	2.7	6.6

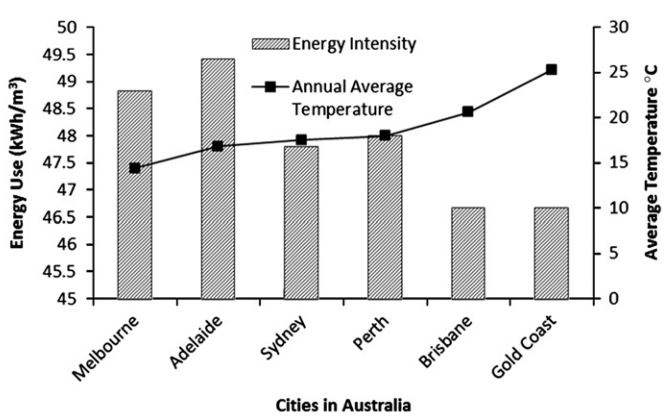

Fig. 16. Energy consumed to heat water in Australia [116,117].

lower temperature, as for showers, energy intensity of showering is significantly lower than that for hot water heating.

Caution is exercised when primary energy such as natural gas is compared with transformed form of energy such as electricity. Power plant conversion of primary [thermal] energy to electricity is assumed to be 33.2% efficient [17–19]. Therefore, the equivalent electrical energy values for natural gas water heaters in Table 6 reflect 33.2% of the actual natural gas energy expended.

The energy expended during end use in a geographic location is dependent on the climate specific to the location [113]. For example, energy consumed for hot water use in residences at various locations in Australia is depicted in Fig. 16. Perth, Melbourne and Adelaide have dominantly cool climates while Brisbane and Gold Coast experience comparatively warmer climates [116].

Kiov and Toode [113] reported that specific energy consumption in Tallin, Estonia for domestic hot water heating consumed an average of 53 kW h/m^2 year. The specific energy consumption for heating water in apartment buildings situated at Tallin ranged from a low range of 30–40 kW h/m^2 year to a high in the range 71–80 kW h/m^2 year [113]. The energy expended also depends on the availability of the primary energy source (such as natural gas) and the location of its reserves. In regions where primary energy is produced, it is easily available. These regions will have low fuel or gas power prices. Similar cost vs. consumption variations in China cannot be examined, since the energy prices are controlled by Chinese government [118].

4.3. *Dish washing*

Dish washing is another major water and energy consuming process at home. There are two scenarios of interest: manual washing and machine washing. Manual dish washing is performed in different ways characterized by the behavior of the individual. There have been several studies on manual dish washing [119,120].

In manual washing, energy for heating wash water is the primary factor, so wash temperature and volume are of importance. People in Europe are reported have a tendency to use hot water to clean [121]. Berkholz et al. [119] reported that energy consumption in manual dish washing was related to quantity of water used. They also found that people concentrated on decreasing their energy and water usage when asked to act as subjects in water-use experiments. This was related to the fact that participation in an experiment has a psychological effect, which led people to limit water consumption. The mean energy consumed for manually washing a load of 12 different tableware (soiled with seven standard types of food) was about 1.7 kW h (electric heating) with an average use of 49.2 l of water in an hour [119]. Similar tests on manual dishwashing were conducted in many regions around Europe, and the results are plotted in Fig. 17. Portuguese people were found to use large amounts of water for washing dishes, thus consuming a lot of energy in the process. Prerinsing of dishes using nozzle jets of water consumed 5.4 kW h/m^3 of energy [94].

Similarly, Berkholz et al. [122] performed energy studies on manual dish washing in the European Union including more than 100 individuals representing Germany, Great Britain, Ireland, France, Portugal, Spain, Turkey, Poland, and Czeck Republic. They also conducted a global manual wash study with experiment participants from Russia, Hungary, and Germany. The results from these studies are tabulated in Table 9. The two studies performed have similar energy consumption values for a unit volume of water consumed in washing dishes. Fuss et al. [120] also proposed that people should be trained for the best dishwashing practices.

4.3.1. *Mechanized dish washing*

Within the last two decades, the machine dish washing in Europe has contributed to electricity savings of 6–40% and water savings of 50–80% as compared to manual dish washing [123].

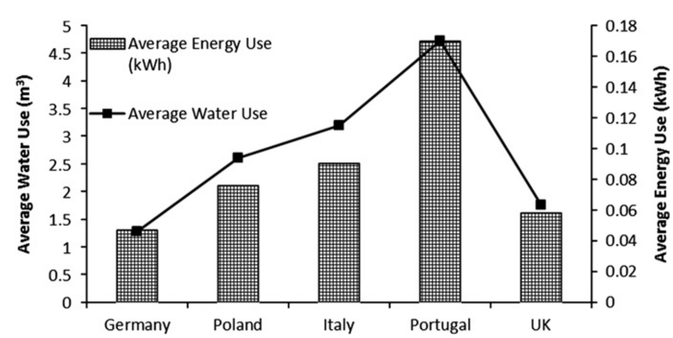

Fig. 17. Average energy and water consumption for manual dish washing in European countries.

Table 9
Characteristics of manual dish washing resource consumption features [117].

Features	European Union Study (2007)	Global Study (2008)
Total number of participants	113	60
Average water consumption (m^3)	0.103	0.113
Average electrical energy used (kW h)	2.5	2.9
Average cleaning performance out of 5	3.3	2.5
Average detergent consumption (g)	35	36.9

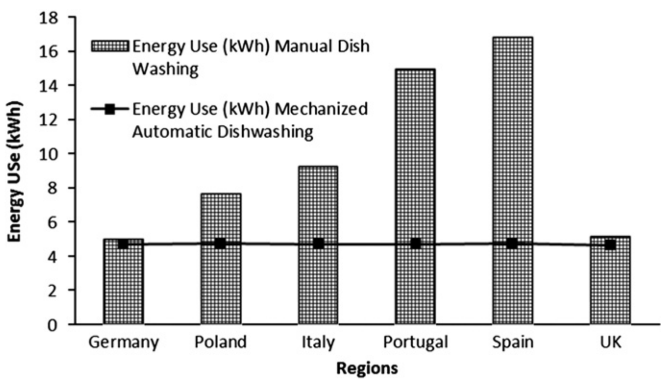

Fig. 18. Comparative study of manual and mechanized dish washing in European countries [125].

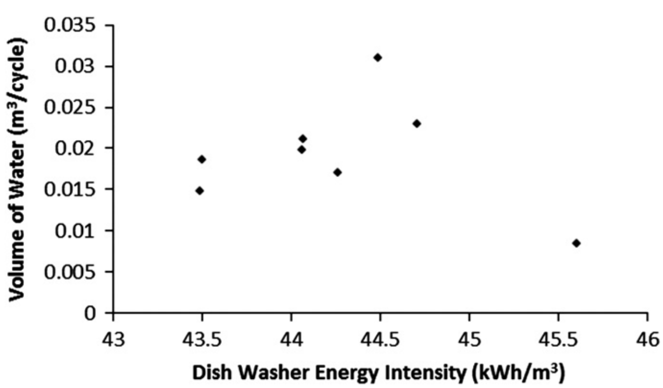

Fig. 19. Scatter of energy consumption ranges for dish washing machines in the US [126].

This improvement was the result of technological improvements in pumping and hydraulics within the dishwashers [124].

Numerous processes operate during the typical machine dish washing cycle. The most obvious is the impulse of the water jets from several spray-arms directly impacting the food based impurities and clearing it from the dishes [124]. Pressure behind the water jets and a large flow rate are a must to accomplish the overall cleaning task.

Fig. 18 plots the energy used per single wash or cycle for mechanized dish washing processes and manual dish washing process. A single wash includes washing a load of 12 different items of tableware soiled with seven standard types of food [119]. The energy values plotted in Fig. 19 include energy for operating the appliance, heating water, detergent production energy, and water and wastewater treatment [125]. The energy savings due to mechanized dishwashing has lowered energy consumption as well as minimized the behavioral influences on energy consumption seen in the manual dish washing process [123]. From Fig. 18, it can be concluded that all mechanized dishwashers have similar energy consumption associated with them.

Hoak et al. [126] performed energy studies on mechanized automatic dishwashers in the US market. Fig. 19 illustrates the results of a portion that study. Energy star qualified dishwashers used 0.02 m^3 of water or less per cycle [126]. According to the US DOE, dishwashers should have at least 0.46 cycles for every kW h of electricity consumed [126]. Energy is consumed to heat water as well as to increase the pumping force with which water is used. A comparison to the average energy consumption of manual dish washing in Europe from Table 9 would indicate that mechanized dish washing in the US consumed comparatively higher energy than mechanized dish washing appliances in Europe.

4.4. Clothes washing

Any clothes washing method uses energy for various tasks including mechanized work or manual labor, and hot water heating and pumping. The end users of a specific community can be characterized by the regional perception of cleanliness and convenience [121]. For example, hot wash is believed to provide better cleanliness according to Europeans but not Japanese [121]. Another example of behavioral influence is that Chinese households did frequent manual washing even if they owned a clothes washer [127]. These perceptions influence the type of clothes washing technology available in the local market.

The energy consumption of clothes washing activity at different locations using mechanized washing machines is illustrated in Fig. 20 [127]. In Fig. 20, the electricity consumption does not take into account the external energy sources expended to heat water. These energy values result from specific designs as well as the behavioral issues mentioned. A review of the type of commercially available clothes washing machines and the corresponding operating temperature ranges at different locations is provided in Table 10.

In China, Japan, North America, and Australia, the electricity consumption for washing clothes is low compared to Europe. This can be related to the corresponding operating temperature ranges of commercially available clothes washing machines in these

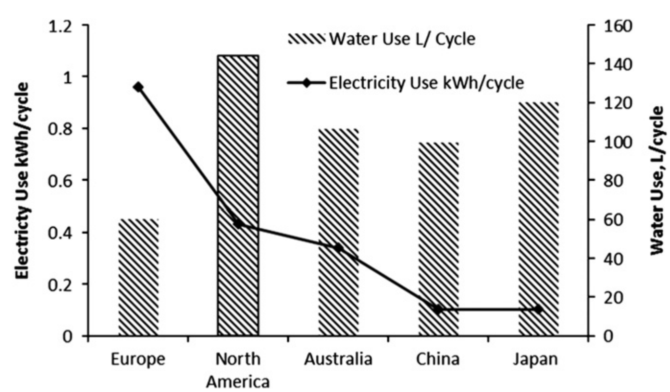

Fig. 20. Variation of electricity and water consumption in washing clothes [127].

Table 10
Types of clothes washers used in different parts of the globe [124].

Location	Type of clothes washer		Wash temperature (°C)
	Horizontal (%)	Vertical (%)	
Europe	98	2	40
North America	10	90	15–48
Australia	25	75	20–40
China	10	90	< 15
Japan	3	97	< 15

regions. Fig. 21 reports the energy requirement of washing machines in the US up to 2006 and also provides an approximate prediction for 2010 [128]. Hoover and Scott [94] reported an average energy consumption of 9.45 kW h/m^3 in clothes washing machines in the US. Comparison of the values reported by Hoover and Scott from 2006 to the values reported by Bole [128] suggests more energy efficient washing machines are coming into the US market with time.

Vertical impeller, cold wash washing machines are widely used in Asia and Australia. Table 11 provides the technical specifications and process features of a cold wash impeller type washing machine from Japan and a hot wash drum type washing machine from Europe, as introduced in China.

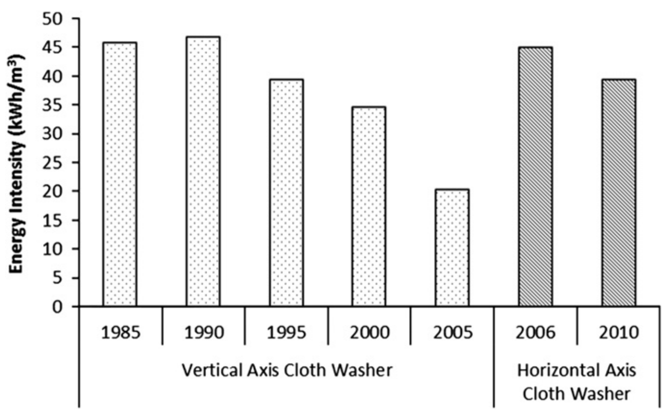

Fig. 21. Energy use by vertical and horizontal clothes washing machines in the US [128].

Table 11
Resource consumption features of washing machines [118].

Product features	Impeller type	Drum
Type	Vertical	Horizontal
Wash temperature (°C)	30 (Cold)	60 (Hot)
Water		
Water use (m^3/cycle/kg of clothes)	0.024	0.014
Annual household water use (m^3/year)	46.8	26
Annual water use (km^3)	1.93	1.07
Electricity		
Electricity use (kW h/cycle/kg of clothes)	0.017	0.23
Annual house hold electricity use (kW h/year)	42	455
Annual electricity use (GW h)	1716	18,769

Advertisers in China have dubbed the drum type washing machine as a water saver and better cleaner while energy as a performance characteristic remains hidden in the advertisements [121]. If hot washing machines are preferred by the consumers in China, a major shift toward energy intensive washing will be in store. This will contribute to increasing residential energy consumption in China. Clear and complete information labeling and details of energy resource consumption becomes a significant parameter in determining energy at the end use since these characteristics may influence consumer decisions on technology use.

From Fig. 22, it is observed that water used per wash cycle in European countries was almost constant among countries. This would hint at a specific washing appliance (horizontal drum) with similar specifications being used across Europe.

The electricity consumed for washing clothes in Asia, USA, and Australia is not a major contributor to total electricity consumption within a household. This trend is not true in case of residential end use in Europe as clearly elaborated in Fig. 23.

Fig. 24 illustrates the energy consumption, water use, and cleanliness offered by different types of washing machines in the Japanese market. Impeller vortex machines were found to have better cleaning capacity when compared to others tested by Katayama and Sugihara [96]. Water consumption was the least in agitator type washing machines. Experimental results reported by Katayama and Sugihara [96] may motivate consumers to choose energy efficient, soil removal efficient, impeller vortex type washing machine to reduce household electricity consumption [129].

Recent reports from the Water Quality Research Foundation have indicated that soft water can help reduce the energy consumption of washing machines [130]. It was also experimentally proved that in order to wash clothes to a specific degree of visual cleanliness or whiteness, soft water required less detergent and water at low temperature [130]. The use of low temperature soft water can reduce the energy consumed at end use to wash clothes. This might also suggest that if the water is softened at the water treatment stage, end users might realize energy savings during clothes washing.

4.5. Cooking

Cooking consumes a major fraction of the overall energy expended in a household. Wallgren and Hojer in 2009 [131] reported that almost 22% of total electricity is used by cooking processes in a Swedish household. This fraction is variable across cultures and nations. No clear documentation is available due to

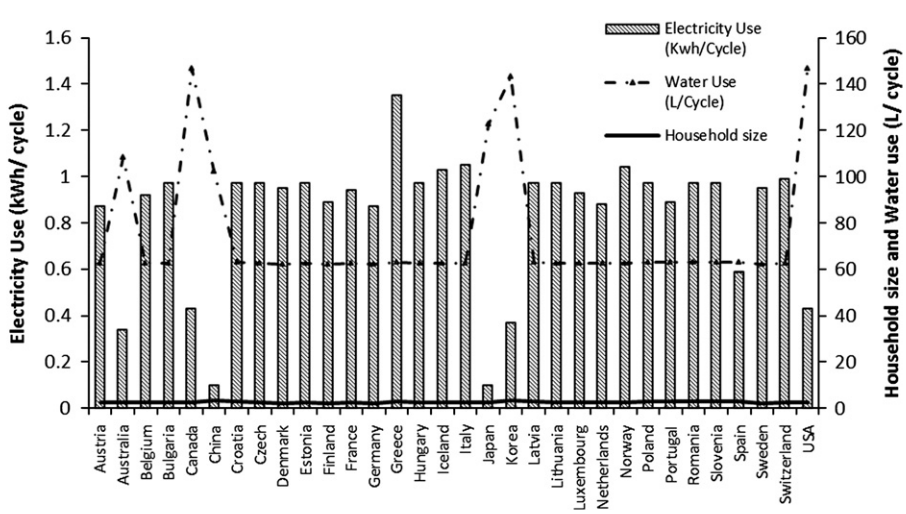

Fig. 22. Electricity consumption and water consumption per clothes washer cycle [129].

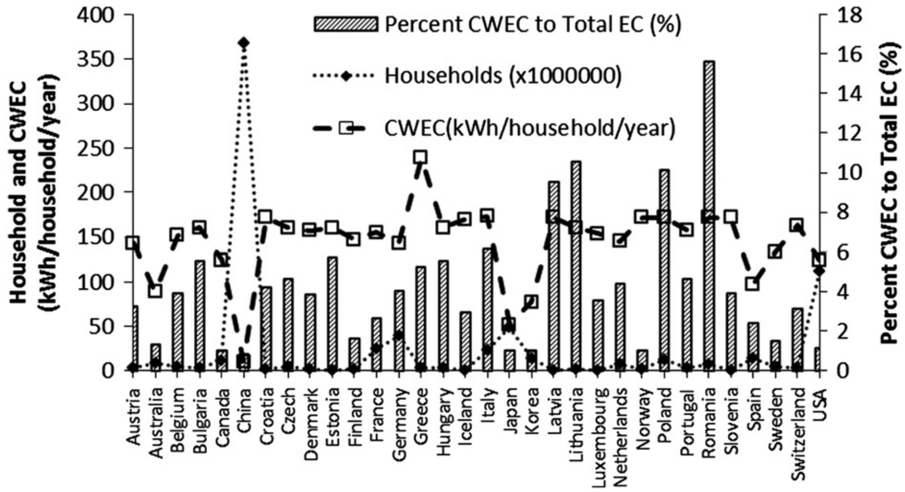

Fig. 23. The clothes washer electricity consumption (CWEC) per household with respect to total electric consumption per household (Total EC) across different countries [129].

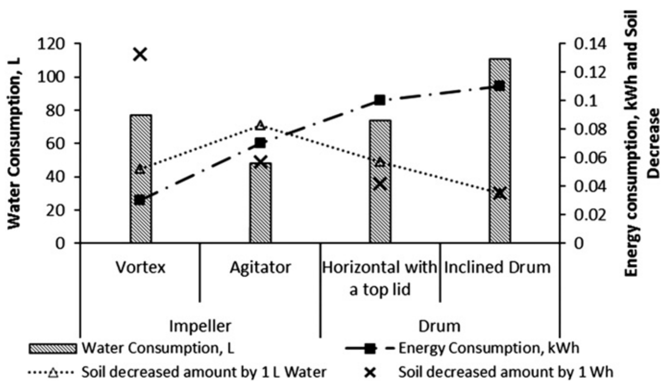

Fig. 24. Results from the experiments conducted by Katayama and Sugihara, 2011[96].

the wide variability and diversity in household food preparation among nations. Also process energy can only be specifically identified to a limited extent and the production energy for food constituents will be very much unknown to the consumer [132]. Similarly chemical conversion and transportation energy is difficult for the end user to comprehend [133].

Many common diets water are intensive and include foods that require boiling in water to make them consumable. Boiling is also a mode of microbial disinfection. Substantial amounts of energy are involved in both bringing water from room temperature to the boiling point (on the order of 0.1 kW h/L) and then in holding it near the boiling point temperature during the cooking process. The energy consumption per unit food mass for boiling cooking water decreased with an increase in volume of water [133]. For example, cooking 70 g of spaghetti in a liter of water consumed electricity at the rate 33.7 kW h/kg of spaghetti while cooking 280 g of spaghetti in 2.5 L of water consumed electricity at the rate 3.75 kW h/kg of spaghetti [133]. Carlsson-Kanyama and Bostrom-Carlsson [133] concluded that cooking large quantities (by mass) of water intensive food was less energy intensive.

The source of energy also played a very decisive role in energy consumption for cooking. Rice is a very common dietary staple around the world. Das et al. [134] performed experiments of cooking rice to a specific edible form using natural liquefied petroleum gas and electricity as source of energy. The results of these experiments are illustrated in Table 12. It can be inferred from these results that energy consumption for cooking rice using natural gas was less energy intensive compared to the use of electricity.

Table 12
Equivalent electricity consumption in cooking rice [131].

Pressure cooking	Water (m^3)	Mass of rice (kg)	Energy consumed (kW h)	Time for cooking (min)
Electrical	0.71	0.3	0.45	16.5
LPG stove	0.71	0.3	0.32	13.5

The major variables contributing to energy consumption in household cooking are volumetric quantity of water used, type of appliance, energy source, time, type of food material being cooked, properties of the food material, water content in the food material, pre-processing of food materials before cooking (sizing or soaking etc.), cultural practices in cooking, level of knowledge of cooking, interaction of different cooking habits, food material compositional mixture ratios and person cooking [132–136].

5. Energy consumption for waste water treatment

The water used in residential, commercial, and industrial end use gets polluted with liquid and solid wastes. Domestic waste water is treated with primary, secondary, and sometimes tertiary treatment stages. Primary treatment processes include waste collection, screening, chemical treatment, grit removal and sedimentation. Secondary treatment processes include aeration, stabilization, suspended growth or fixed film processes, clarification, and membrane bioreactor processes. Secondary processes only remove 20–30% of nitrogen from the wastewaters. Higher nitrogen and phosphorus removal can be met by use of tertiary processes such as nitrification–denitrification. These processes can consume substantial amounts of energy. The energy consumed by these processes depends on size of the plant, the location of the treatment plant, the population served, the type of impurity, the type of treatment process, the end users of water in the area, quality of water the treatment plants receive, quality of treatment required for water discharge, economic status of the wastewater treatment plant, and the experience of the plant managers [20,45,46,48]. The type of impurity to be removed is the major parameter that drives energy consumption in waste water or water treatment.

5.1. Primary treatment

Primary treatment includes screening, size reduction and inorganic suspended solids removal process. These are low energy

intensity processes. Primary sludge pumping is the most intensive primary treatment process. Influent waste water pumping and collection in California ranged from 0.003 to 0.04 kW h/m^3 [65,137]. Raw sewage collection and pumping consumes an average of 0.04 kW h/m^3 energy in the USA. Wastewater pumping in New Zealand ranged from 0.04 to 0.19 kW h/m^3 while it was in the range of 0.02–0.1 kW h/m^3 in Canada [58,31]. The grit removal processes basically rely on settling of grit or grit collection in an inverted conical vessel with a grit discharge. The inorganic grit targeted at this stage has an approximate specific gravity of 2.65 [45]. Energy is consumed to drive the grit pumps, which conveys grit to a dumping place. Once the grit is removed, wastewater is sent to the primary sedimentation tank. Roughly 60% of suspended organic solids as well as 30% BOD (biochemical oxygen demand) is removed in the primary sedimentation tank [45]. Energy expended for the sedimentation is meager, in the range of 0.008–0.01 kW h/m^3 [138]. Total energy consumed for this primary treatment in Australia ranged from 0.01–0.37 kW h/m^3 [117].

Chemicals are also sometimes used to increase the biological oxygen demand as well as to reduce the organic load in the sludge. Rapid mixing, chemical pumping, polymer pumping, chemical transfer pumping are some of the pumping processes when chemical addition is performed. Poor primary treatment design and operation could affect the overall energy footprint of the waste treatment plant.

5.2. Secondary treatment

At this stage, wastewater with remaining colloidal organic impurities such as proteins and dissolved organic matter, such as carbohydrates, enters secondary treatment. Biological treatment is predominant in this stage of wastewater treatment. This induces the need for enough oxygen to run the processes. Mechanical or surface (used in continuously stirred tank) and diffused (used in plug flow) aeration systems are used for this purpose. Aerators also help proper mixing of the waste sludge apart from providing more oxygen. Aeration blowers consume half the energy consumed by diffused aeration secondary treatment systems [48]. Energy efficient air blower aeration devices in Wisconsin consumed 0.026–0.04 kW h/m^3 [139]. The average consumption of mixing and pumping action at this stage for a 1000 m^3 sewage plant is in the range of 0.012–0.033 kW h/m^3 [138]. Organic impurities are acted upon by heterotrophic microorganisms present in wastewater within aerator systems in the presence of oxygen. For conventional aeration processes the oxygen concentration is between 0.5 and 1.0 mg/L while in extended aeration 1.0 and 2.0 mg/L of oxygen is necessary [45].

There are many available aeration technologies and devices in the market, including static tube diffused aerators and fine bubble flexible diffusers [48]. Fine bubble flexible diffusers consume only half the energy consumed by static tube diffused aerators [48]. Another type of diffuser is the porous diffuser, to provide fine pore aeration. Fine pore diffusers produced oxygen at the rate 1.2–2 kg/kW h and consumed approximately 0.037 kW h to aerate a cubic meter of water [45,139]. An energy intensity of 0.055 kW h/m^3 was measured in ultrafine porous diffusers by Toffey [139]. Surface aerators in India produced 1.2–2.4 kg of oxygen per kW h of electricity consumption [45].

Oxidation results in the breakdown of organic material to carbon dioxide and water, and further produces flocculating microbe biomass. Once the microbial biomass reaches the endogenous phase, it starts producing exocellular polymers which have binding properties [45]. This helps colloidal biomass to aggregate and flocculate. Once this action takes place, the residual wastewater with the flocculation biomass is sent to a secondary sedimentation tank. Some part of the flocculating biomass settles under gravity and is removed from the wastewater system here. About 30% of this removed biomass is recycled back to the aerator while the rest is sent to the sludge treatment system [45]. This recirculation is performed to maintain the desired biomass concentration in the aerator. Recirculation pumping in activated sludge processes was reported to consume an average of 0.011 kW h/m^3 of energy [138]. Digestion is the term used to define these processes of converting the organic solids in the sludge treatment tanks to more inert forms suitable for disposal. The energy consumed by aerobic digestion process in a biological nutrient removal sewage treatment plant in Australia was reported to be approximately 0.5 kW h/m^3 [140].

Aeration systems like wetlands and land treatment in China had an average energy consumption of 0.253 kW h/m^3 while aeration processes in the UK were reported to consume an average of 0.13 kW h/m^3 of electrical energy [138,141]. Michaud [142] classifies five types of natural wetlands, namely marine (wetlands with seawater), estuarine (freshwater and seawater mixing regions), riverine (moving fresh water), lacustrine (closed pond structures), and palustrine (forests, swamps, marshland etc.). The basic function of wetlands includes water treatment, ground water recharge, protection from floods, act as plant, marine or animal habitat and acts as buffers for dissipating kinetic energy of water [143]. These wetlands are also used to enhance biological treatment of wastewater. They functionally enhance processes like phytoremediation and include natural growths such as reed beds, which help filter water [143].

Additional aeration processes include oxidation ditches, which help to improve the oxygen content of wastewater. Oxygen content helps the removal of nitrates from the wastewaters [48]. High oxygen demand and long residence time increases energy intensity of oxidation ditches more than activated sludge processes [144]. From Table 13, it is seen that in Australia, China, and Japan, aeration or oxidation ditch processes were more energy intensive than activated sludge processes [141,144]. Activated sludge processes involve suspensions of active microbial cultures in a reactor, where air or oxygen can be introduced to sustain microbial activity. These systems are suspended growth systems where microbial bio-film surfaces help in breaking down the organic and inorganic constituents of the wastewater flooded on these surfaces. Processes such as return sludge pumping and thickening are included in activated sludge wastewater treatment plants.

The least energy intensive aeration systems are lagoons and trickling filter (fixed film) process when compared to other secondary treatment processes listed in Table 14. Fixed film or attached growth systems such as a trickling filter, rotating biological contractors, fluidized bed attached or submerged systems

Table 13
Energy intensity (kW h/m^3) of secondary wastewater treatment suspended growth processes from different parts of the world.

Treatment Technique	Australia	China	USA	Japan	References
Lagoons		0.253 (avg)	0.09–0.29		[141,145]
Activated sludge	0.1 (avg)	0.269 (avg)	0.33–0.60	0.30–1.89	[48,141,144]
Oxidation ditch	0.5–1.0	0.302		0.43–2.07	[141,144]
Membrane bio-reactors	0.10–0.82	0.33 (avg)	0.8–0.9; 0.49–1.5		[48,141,146]

have a granular growth media for promoting microbial growth [45]. These systems have a distribution arm which helps the wastewater to be distributed evenly over this media. Microbes would break down the flocculating biomass. The biomass after its breakdown is sent to the sludge treatment tanks while the effluent is recycled to provide kinetic energy to the distributor arm. Recirculation pumping in trickling filters was reported to consume an average of 0.021 kW h/m^3 of energy [138].

Anaerobic digestion usually takes place in three steps. First, hydrolysis of organic mass and proteins occur in the microbial media. Enzymes produced by anaerobic microbes break down these organic and protein macromolecules into small digestible forms. Second, these molecules are decomposed into small fatty acids. This decomposition is performed by anaerobic bacteria. Finally, methane producing bacteria digest these fatty acids, resulting in the formation of methane, ammonia, hydrogen sulfide, and carbon dioxide in gaseous form [148]. This gas has a fuel value of approximately 6.2 kW h/m^3 [149]. Anaerobic digestion has the capacity to deliver gas at the rate 35 m^3/d person [149]. The new biological wastewater purification facility in Singapore installed by Siemens produces methane enough to supply energy equivalent to its consumption, around 0.25 kW h/m^3 [150]. Digested sludge (after processing) in many countries is used as a soil conditioner for agricultural farms [45].

From Fig. 25, it is clear that there is a drastic decrease in the specific energy consumption of the plant with an increase in volume. Second there is a decrease in the energy intensity of digestion with increase in size. Trickling filters are more energy intensive than waste digestion in large tricking filter waste water plants, with size greater than 4×10^4 m^3. The average electricity consumption of digestion processes for a 1000 m^3 plant in the UK was 20 kW h while trickling filters of the same volume capacity consumed 21 kW h [138]. From Fig. 26, it is seen that aeration in activated sludge treatment plants has similar energy requirements, irrespective of size.

Membrane bioreactors are designed to operate at comparatively high suspended solids concentration compared to activated sludge processes. Advantages over the activated sludge are comparatively higher loading rate, short detention time, operation at low

Table 14
Energy intensities of secondary wastewater treatment processes in the USA [145,147].

Waste water treatment	Equivalent energy intensity (kW h/m^3)
Lagoon	0.09–0.29
Trickling filter	0.18–0.42
Activated sludge	0.33–0.60
Advanced wastewater treatment	0.31–0.40

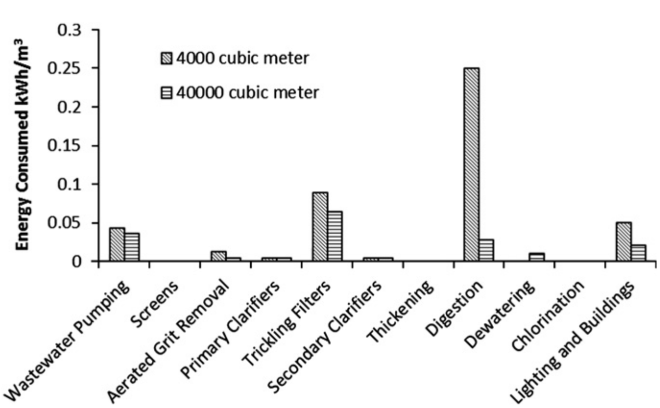

Fig. 25. Energy use for trickling filters wastewater plants [48].

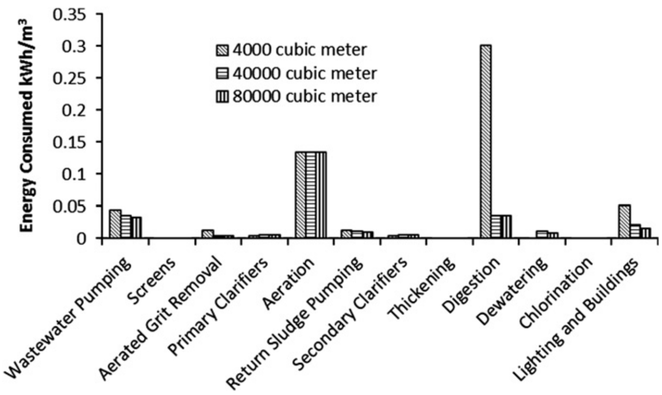

Fig. 26. Energy use for activated sludge wastewater plants [45].

dissolved oxygen conditions, better effluent quality (5 mg/L of BOD, 30 mg/L COD, turbidity <1 NTU) and no requirement for clarifiers [23,45]. Membrane bioreactors help to separate the solids from the mixed digested sludge. There is a need to overcome the trans-membrane pressure (7–65 kPa) across these micro or ultrafiltration devices to filter the waste activated sludge [23]. This adds to the energy requirements for membrane bioreactors. From Table 13, it is clear that membrane bioreactors are components which are major energy consumers in secondary waste water treatment. Radcliffe [140] reported that Australia used a combination of micro filtration as a pretreatment step with nanofiltration and reverse osmosis in its sewage treatment plants. These membrane processes consume 0.41 kW h/m^3 and 0.82 kW h/m^3, respectively, with a water recovery rate of 74–83% and 74–82%, respectively [140]. At this stage, microfiltration independently consumes 0.11 kW h/m^3 with a water recovery in the range of 92–95% [47]. Dual membrane filtration plants in Gold Coast Australia consumed 0.4 kW h/m^3 [140].

Finally, the effluents from the activated sludge or trickling filter or membrane filters are disinfected as required. Chlorination as well as ultraviolet disinfection methods are practiced around the world. The energy requirements for chlorination of these effluents are similar to those for drinking water disinfection processes (Table 3). Recently health issues due to chlorine disinfection by products have made ultraviolet disinfection more promising. Ultraviolet disinfection within a biological nutrient removal sewage treatment plant in Australia consumed 0.05 kW h/m^3 [140]. The energy requirements to disinfect unit quantities of wastewater by using UV appliances are provided in Table 15.

Secondary wastewater treatment in the USA consumes energy in the range of 0.16–0.45 kW h/m^3 [151]. Table 16 provides a review of the mean electrical energy consumption by secondary waste treatment plants in several countries.

5.3. Tertiary treatment

The energy consumed by waste treatment plants varies depending on the final, high level treatment applied to the effluents, and rises if the effluents are treated to potable water standards.

Wastewater contains organic biodegradable compounds such as carbohydrates, proteins, and lipids. Once most of the organics are removed by secondary treatment, the carbonaceous oxygen demand or BOD is reduced. This coincides with nitrogen becoming the major center for oxygen demand or chemical oxygen demand or COD. In this stage, heterotrophic microbes are outnumbered by autotrophs [20,45]. In particular, the proteins contain carbon, hydrogen, nitrogen, and oxygen in the form of amino acid polymers. Permitted levels of inorganic nitrogen in

Table 15
Energy consumption of UV disinfection processes in a US wastewater treatment plant [48].

Disinfection appliance	Additional appliances	Energy range ($kW\,h/m^3$)
UV-open channel reactor	Low pressure mercury lamp	0.021
UV-open channel reactor	Low pressure high output mercury lamp	0.015
UV-open channel reactor	Medium pressure mercury lamp	0.066

Table 16
Mean energy consumptions of secondary wastewater treatment.

Countries	Australia	China	Japan	USA	Sweden
Energy ($kW\,h/m^3$)	0.305	0.29	0.304	0.2	0.42
References	[117,140]	[141]	[144]	[48]	[141]

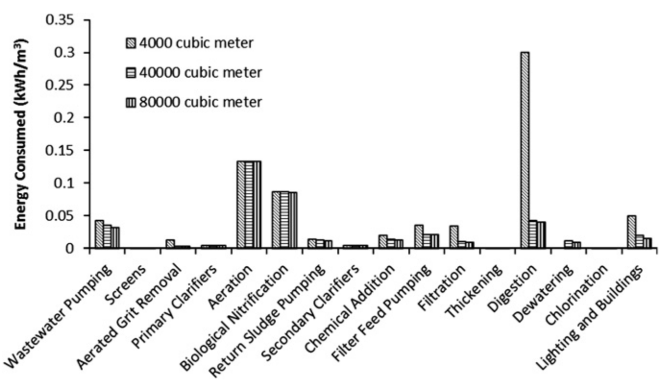

Fig. 27. Energy use in advanced wastewater treatment plants [48].

treated waste water should be less than 0.3 mg/L [45]. Water polluted with nitrates promotes prolific algal growth and when consumed by humans may cause methemoglobinemia (blue baby syndrome) [45]. The proteins are broken down to amino acids by autotrophic microbes and further degraded by deamination to ammonia. Ammonia is oxidized to nitrites; which are further oxidized to nitrate by nitrifiers in the biological nitrification process [20,45]. Nitrate is converted to nitrogen by *nitrobacter* in an aerobic process of addition of methanol or anaerobic process by addition of ammonia [45]. Sometimes secondary processes are unable to achieve complete removal of ammonia.

Advanced water treatment with nitrification consumed energy in the range of 0.40–0.50 $kW\,h/m^3$ [147]. Independent energy consumption of biological nitrification is provided in Fig. 30 which plots energy use of advanced wastewater treatment plants (with nitrification) in the USA. This high energy range also points to the temperature range in which anaerobic processes take place. Utilities in USA use anaerobic digestion of the waste sludge with the help of thermophillic microbes which work at 54–55 °C [48]. The energy intensity of anaerobic digestion is around 0.28 kW h per cubic meter of wastewater [151]. In Japan, advanced wastewater treatment is highly energy intensive with an energy consumption range of 0.39–3.74 $kW\,h/m^3$ [144]. The large energy consumption values in Japan are related to the small size of the decentralized wastewater treatment plants [144].

Lagoons also offer further opportunities to treat and aerate the wastewater and remove excess nitrates in tertiary water treatment before the treated wastewater or sludge is discharged to the receiving environments (ocean, rivers or ground recharge). They are low intensity processes with an energy consumption range of 0.09–0.29 $kW\,h/m^3$ [145]. Further removal of the suspended solids and possible nitrates need to be carried out with filtration (granular) processes, depicted in Fig. 27.

Sludge has high water content as well as solids. These solids, if dry, are a potential source of energy. Dewatering and thickening are the two processes to remove water from the sludge. The dewatering stage is reported to consume 0.3 $kW\,h/m^3$ [140]. Microbiology as well as minimization of contaminant in the wastewater is very important at this stage. Nitrates and phosphate are chemicals that need to be removed completely before releasing the wastewater to the receiving environments.

Phosphorus removal is necessary since phosphorous promotes the growth of algae in fresh water receiving environments. Permitted levels of phosphate in treated waste water should be less than 0.015 mg/L of soluble orthophosphate [45]. Wastewater reverse osmosis processes are efficient in phosphorus removal, but are energy intensive. In Spain, the Abreba wastewater treatment plant reverse osmosis system consumed 0.8 $kW\,h/m^3$ of electricity [59]. Similarly, the RO wastewater treatment system at Marafiq, Saudi Arabia consumes 1.6 $kW\,h/m^3$ [59]. Gnirss and Dittrich [152] studied microfiltration membranes effective at phosphorus removal. A microfiltration system with polymer membranes (Memtec-10 m^2, USF Memcor, Derbyshire, UK) consumed 0.14 $kW\,h/m^3$ of energy; a different system using ceramic membranes (MemBrain-11.2 m^2, Zenon GmbH, Dusseldorf, Germany) consumed 0.06 $kW\,h/m^3$ [152].

The volume of the wastewater plant plays a major role in setting the energy requirements for wastewater treatment processes. With an increase in size of the plant, the overall energy specific consumption by the individual processes diminishes. From Fig. 28, it is found that advanced tertiary treatment has comparatively higher consumption of energy than primary and secondary [155]. The overall energy intensity for tertiary water treatment in Australia was in the range of 0.23–10.55 $kW\,h/m^3$ [140].

The energy consumption of conventional wastewater treatment plants in Arizona ranged from a low of 0.09 $kW\,h/m^3$ at the Roger Waste Water treatment Plant to a high of 4.04 $kW\,h/m^3$ at Mt. Lemmon in Arizona [94]. Wastewater treatment in Utah consumed 0.8 $kW\,h/m^3$ including waste water pumping and collection consuming 0.56 $kW\,h/m^3$ [154]. Kneppers et al. [58] reported waste water treatment studies from four different cities in New Zealand and found that their energy consumption was in the range of 0.32–0.88 $kW\,h/m^3$. The conventional municipal wastewater treatment sector in the USA consumes an average of 0.43 $kW\,h/m^3$ of energy, which is similar to the consumption of New South Wales, Australia (0.362 $kW\,h/m^3$), Ontario, Canada (0.46 $kW\,h/m^3$), Taiwan (0.41 $kW\,h/m^3$), and New Zealand (0.49 $kW\,h/m^3$), respectively [13,31,58,140,151]. It is important to note that climate also plays its part to influence energy consumption. Radcliffe [140] reported that the New South Wales plant in Australia consumed 0.418 $kW\,h/m^3$ in 2002 compared to 0.362 $kW\,h/m^3$ in 2001. This increase was due to the increased waste water pumping in New South Wales, Australia following unprecedented rainfall events in February 2002 [140].

6. Energy consumption of wastewater reuse and recovery.

The concept of wastewater recycling is becoming more accepted and has been adopted in several countries recently. Israel and Singapore recycle about 87% and 50% of their wastewater, respectively; in contrast, the US reuses only 8% of its treated wastewater [155,156]. The Bedok and Kranji recycled water treatment plants (NEWater Factories) in Singapore consume energies in the range of 0.72–0.93 $kW\,h/m^3$ to produce drinking water from municipal effluent [38,157]. Seah et al. [158] reported that these NEWater factories removed more than 97% total dissolved salts, more than 94% ammonia, more than 99% total organic carbon, and

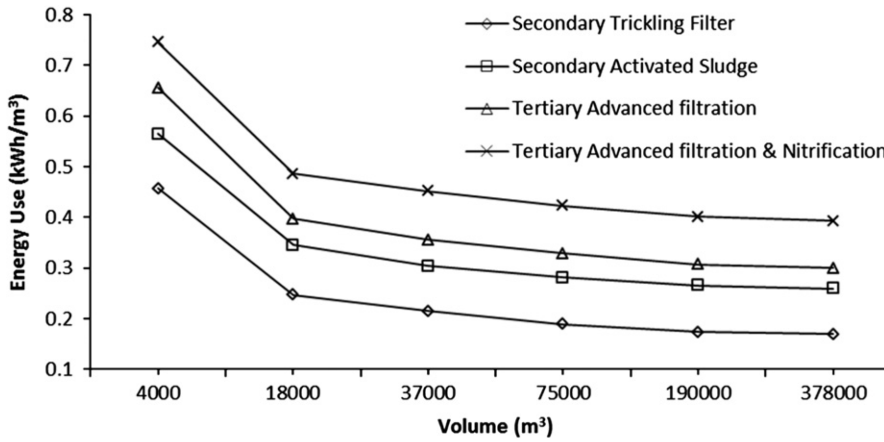

Fig. 28. Secondary and Tertiary treatment energy use as a function of waste water volume processed per day [153].

Table 17
Waste water recycling and energy consumption in California.

Californian waste water recycling plants	Energy consumption (kW h/m^3)	References
Inland Empire Utility Agency, Chino	0.33	[38]
West Basin Municipal Utilities Department	0.57	[38,161]
Santa Clara Valley Water District	0.73	[65]
North City Recycling plant	0.76	[65]
San Diego Recycling plant	1.21	[34]
Orange County Recycling plant	1.86	[34]

achieved a permeate turbidity of less than 0.1 NTU (within the current USEPA Drinking Water Standards and WHO Guidelines for Potable water quality). Residential wastewater reuse consumed 0.27–1.2 kW h/m^3 of electrical energy, while large scale potable waste water pumping and recycling with reverse osmosis process (no energy recovery) consumed 2.8–3.8 kW h/m^3 of electricity in Australia [36,159,160].

Reclamation of wastewater in the cities of Phoenix and Tucson, Arizona consumed 2.4 kW h/m^3 and 1.2 kW h/m^3 of energy, respectively [94]. Recycled water pumps in California consumed energy in the range of 0.21–0.39 kW h/m^3 [27]. Wastewater was treated at an energy expense of 2.9 kW h/m^3 for usage as irrigation water and at energy of 3.1 kW h/m^3 for usage as potable water at Laguna Beach, California [65]. The total amount of energy consumed for recycling water at South Coast and San Francisco in California was approximately 0.92 kW h/m^3 [27]. Reverse osmosis processes in recycling waste water in Australia consumed approximately 1.05 kW h/m^3 of energy [38]. A list of other Californian recycling plants and their electricity consumption is given in Table 17.

A large quantity of water is used for oil/gas exploration processes [162–165]. Some of this large quantity of water returns back to the surface loaded with chemicals including organic compounds, metallic impurities, injection fluid chemicals, and silt or soil [162–165]. The regulations, disposal, cost to haul water, availability of fresh water source for hydrocarbon extraction, renewable or non-renewable water sources depletion, ground water quality deterioration, as well as geo-spatial changes are some of the main drivers for produced water management (PWM) [166]. Various technologies are available for PWM, many of which are variants of municipal treatment systems. Some of these technologies are plotted corresponding to their operating feed total dissolved solids (TDS, in mg/L) and energy intensities (kW h/m^3) in Fig. 29. With increasing in TDS in the produced water, the amount of energy required for treatment increases.

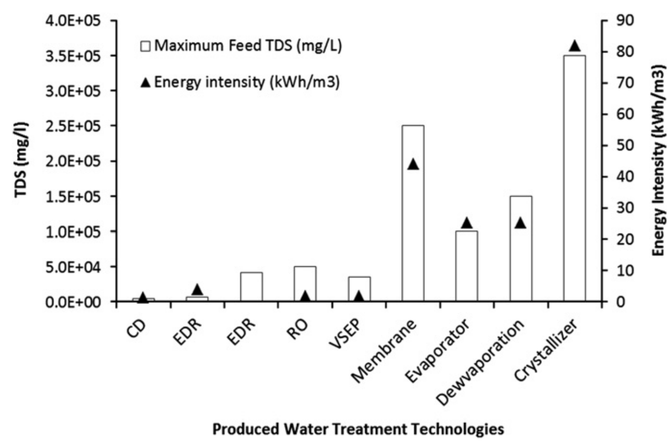

Fig. 29. Energy intensity for some of the produced water treatment technologies [162,164,165,166].

Table 18
Energy intensity of different types of constructed wetland systems that can be used for produced water treatment [167].

Water treatment methods	Energy intensity (kW h/m^3)
Surface flow wetlands	0.12
Sub-surface flow wetlands	0.13
Facultative lagoon + rapid infiltration	0.14
Facultative lagoon + overland flow	0.19
Aerated subsurface flow wetlands	0.19
Tidal flow wetlands	0.21
Carrousel oxidation ditch	0.53
Sequencing batch reactor	1.17
Living machine treatment system	1.54

Wetlands also play as an important role as recycling treatment low cost alternatives for produced water recycling and treatment. Davis et al. [167] reviewed the energy intensities of different types of constructed wetlands techniques used for produced water treatment. Some results of the review are listed in Table 18.

7. Energy intensity for irrigation in agriculture

Agriculture is a major consumer of water worldwide, as seen clearly from the data in Table 1. Energy consumption and irrigation in agrarian economies are intertwined with each other. Some authors refer to this relationship as the energy–irrigation

Table 19
Inputs for Canola production in Iran [169].

Item	Units	Consumption for irrigated (unit/ha)	Consumption for rain-fed (unit/ha)
Human labor	h	106.5	73.4
Machinery	kg	11.6	11.8
Diesel fuel	m^3	0.1	0.101
Biocides	kg	100.5	101.6
Chemical fertilizers	kg	199.5	184.5
Farmyard manure	kg	985.7	1746.8
Irrigated water	m^3	1511.1	0
Electricity	kW h	1207.3	0
Seeds	Kg	9.1	8.1
		Output (unit/ha)	Output (unit/ha)
Canola produced	kg	2349	2114

nexus, the electricity–irrigation nexus, or the diesel–irrigation nexus [10]. The energy expended to irrigate a field is dependent on the amount of water pumped, area of the field, soil characteristics of the location, geology, slope, crop varieties or cropping patterns, precipitation or climate at the location, temperature, type of irrigation, irrigation scheduling, application effectiveness, pumping system type, pressure requirement at the point of use and energy cost [24,143].

Human behavior also plays its part in influencing energy consumption. Farmers' desire to obtain higher yields in water scarce regions influences the use of fertilizers. In water abundant areas, farmers increase labor to intensify irrigation in order to get higher yields [168]. This can lead to overexploitation of ground water resources in water abundant regions, and thus lead to pumping from increasing well depth. Therefore, farmers' behavior clearly influences energy use in irrigation. This behavior can be related to the phenomenon that irrespective of crops, agriculture was more productive under irrigated than rain-fed (no irrigation) conditions [168,169]. This is also confirmed by data on electricity consumption in Table 19. Table 19 also quantifies all the direct energy inputs such as human labor, water, seeds etc. and also indirect energies such as manure, chemicals, fuel etc. [169].

7.1. Energy expense for surface irrigation

Surface irrigation is irrigation by flooding the field with water pumped from a well or a surface reservoir, canal, or channel. Surface irrigation is less energy intensive when surface water is used instead of ground water (see Section 2). This is confirmed from Fig. 30, which plots energy use per cubic meter of water supplied by surface irrigation at four different locations in the California Central Valley [170]. Surface water availability in the Sacramento River and Sacramento-San Joaquin delta is much higher than ground water availability [170]. Further, the lift required to pump water varies considerable: at the Sacramento River, Sacramento- San-Joaquin Delta, San Joaquin, and Tulare Lake, the lift was 18.6 m, 29.5 m, 38.7 m and 57.3 m, respectively, in 1977 [170]. Ground water availability in San Joaquin and Tulare lake was comparatively higher than the surface water available there, despite the higher lifts involved [170].

Surface irrigation from a surface source may be assumed to consume no energy, while a 3 m deep ground water source was found to consume 0.024 kW h/m^3 of energy [153]. Surface or furrow irrigation by pumping water from a river at a pressure of approximately 1 bar consumed 0.045 kW h/m^3 and by pumping water from a bore well at a pressure of 4.4 bar pressure consumed 0.2 kW h/m^3 in Tasmania, Australia, respectively [171,172]. Surface irrigation using either surface or ground water pumping consumed energy between a low range of 0.138 kW h/m^3 and a high 0.9 kW h/m^3 in Spain [38].

7.2. Energy variations in pressurized irrigation: Micro irrigation/sprinklers/hoses

Technology, innovation, and efficiency requirements have helped modernize irrigation systems from open channel systems to pressurized systems. Energy consumption in sprinkler irrigation is comparatively higher than surface irrigation [173]. A comparison of the data in Figs. 30 and 31 provides an insight into the differences in energy consumption for pressurized systems such as sprinkler irrigation as opposed to surface irrigation. Fig. 31 represents the energies for irrigating alfa–alfa, cotton, and vegetables in California using sprinkler irrigation.

From Fig. 32, in sprinkler irrigation systems there is an increase in energy use per unit volume with the decrease in the amount of water. Similar behavior is not seen in drip irrigation systems (Fig. 33), which provide water to the root zone of the plant and have their water outlets near the roots. Energy consumption for drip irrigation ranged from 0.32 to 1.1 kW h/m^3 while for sprinkler irrigation it is 0.6–1.3 kW h/m^3 [173,174]. Comparatively higher energy intensity is observed for sprinkler systems in Spain as opposed to California. Conclusions could not be drawn on the cause of the different energy intensities at these two locations. From Abadia et al. [173] the type of crops that are grown in study zones of the sprinkler experiments in Spain are unclear.

A travelling gun irrigation system operates from 4 to 7.5 bar and consumes an average energy of 0.61 kW h/m^3 of water applied or 3.15 kW/L of fuel used [175]. Studies on traveler irrigation systems from Australia operating at approximately 8.3 bar using river (surface water) pumping, 8.8 bar using bore well pumping and 11.8 bar discharge pressure have operational energy consumption of 0.38 kW h/m^3, 0.4 kW h/m^3, and 0.54 kW h/m^3, respectively [171,172]. Fig. 34 illustrates energy intensities of different irrigation technologies in use for irrigation in Australia.

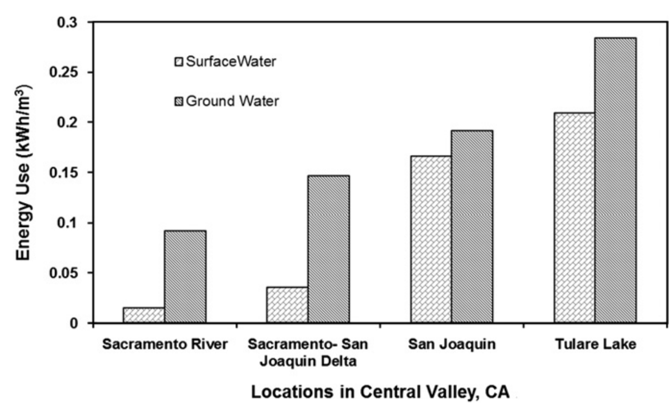

Fig. 30. Surface irrigation energy intensity at different locations in Central Valley, CA [170].

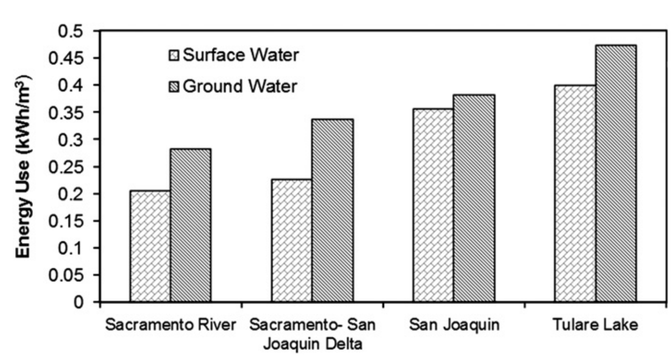

Fig. 31. Sprinkler irrigation energy intensities at different locations in Central Valley, CA [170].

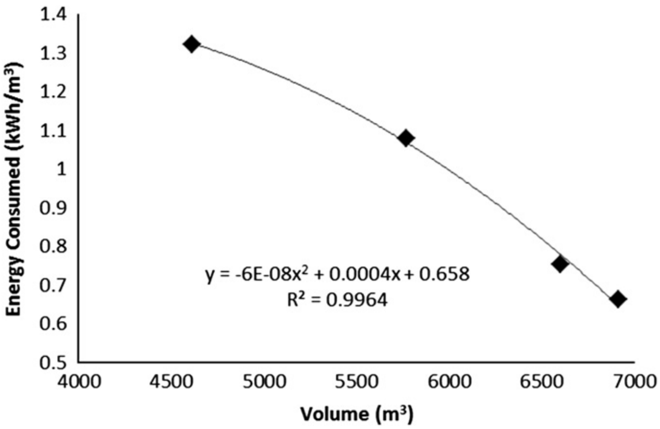

Fig. 32. Energy use and water application in sprinkler irrigation systems in Spain [173].

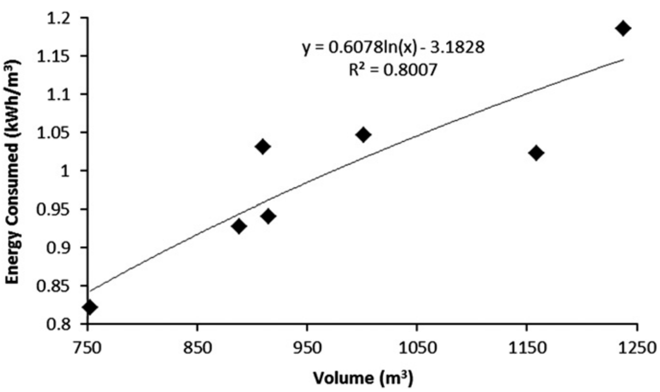

Fig. 33. Energy use and water application in drip irrigation systems in Spain [173].

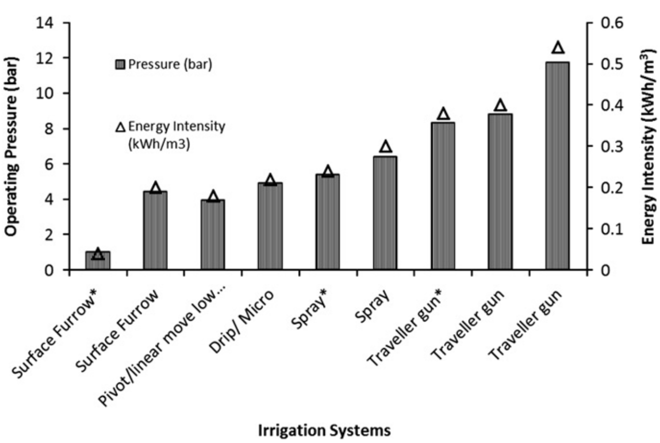

Fig. 34. Energy intensities for irrigation systems in Australia [172]. Here, ∗ denotes irrigation systems that pump water from a surface source instead rather than a ground water source. All other systems pump ground water.

Griffiths-Sattenspiel and Wilson [153] reported an energy intensity of 0.23 kW h/m^3 for pumping in a sprinkler irrigation system, while an energy intensity of 0.167 kW h/m^3 was reported for a drip or micro irrigation system. The difference is because drip irrigation systems operate at much lower pressure range (0.55–1.37 bar) than permanent overhead sprinkler systems (3.1–4.8 bar) [176].

The sprinkler or pressurized irrigation systems have been characterized according to their operating pressure. High pressure, intermediate pressure, and low pressure sprinkler irrigation systems operate at 4.8–9.6 bar, 2.4–4.8 bar and 1.4–2.4 bar, respectively [177]. The most convenient and portable set is the small overhead system (2.4–3.8 bar). Sprinkler systems using perforated pipes operate at 0.47–2.38 bar pressure. Finally there are two types of under tree sprinkler systems discharging water at 0.06–0.25 L/s. They are a gravity fed system, which operates at 0.7–1 bar, and a normal system which operates at 1–2.4 bar [177]. Spray irrigation systems that pump river water at 5.4 bar pressure expended 0.25 kW h/m^3 for their operation, but spraying systems using water lifted from bore wells at a pressure of 6.4 bar pressure consumed approximately 0.3 kW h/m^3 [171,172]. Permanent overhead sprinklers which operate at 3–4.8 bar are also used for frost protection and for pesticide application [172]. Table 20 provides recorded values of energy for irrigating a farm using different irrigation systems. Energy consumption by pivot or linear move irrigation systems used in Australia, which operated at approximately 4 bar, was 0.18 kW h/m^3 [171,172]. Table 20 provides reported values of energy for irrigating a farm using different irrigation systems.

7.3. Energy requirements for irrigation

Energy consumption for irrigation in agriculture can also be characterized according to the crop grown. Each plant has distinct regimes of pollination and related growth or seed production. Productivity of crops is dependent on timely irrigation and judicious application of energy in direct (human labor, water etc.) and indirect (manure, chemicals, machinery etc.) forms. Recently, the need to study the energy consumption and energy output of different fruit and vegetable crops across the world has been stressed [176], particularly in order to understand the energy used to irrigate crops for efficient production. The following sections will review the energy expenditure in irrigating some of these crops.

7.3.1. Fruits and vegetables

Drip irrigation has been practiced in India since 1980 [25]. Crops have been gradually shifted from conventional surface irrigation to drip irrigation. This shift has been mostly related to water scarcity, the low energy consumption characteristics of drip irrigation, and crop change. From Table 21, it is clear that a large amount of electricity can be saved by installing a drip irrigation instead of a surface irrigation system.

Recently sugarcane has emerged as a biofuels crop, and so its energy and water requirements are of interest. Data from Iran include sugarcane and several fruit crops: orange, apple, mandarin, and kiwi fruit. Table 22 provides the equivalent energy consumption to (surface) irrigate these fruit crops. From Table 22 sugarcane is observed to consume comparatively more water among the fruits crops, but the least energy for irrigation. Overall,

Table 20
Energy requirements and water use in different types of irrigation systems [178].

Type	Irrigation system	Energy consumption (kW h/ha yr)	Water irrigated (m^3/ha yr)
Mobile			
	Sprinkler	800	12,000
	Nozzle carrier	400	9,000
Stationary			
	Central pivot nozzle	340	9,000
	Linear lateral nozzle	340	9,000
	Side roll irrigation tube	650	12,000
Row sprinkler			
	Movable hose	650	12,000
Micro-irrigation			
	Drip system	135	8,400

Table 21
Electricity use for drip and surface irrigation of crops grown in India [25].

Electricity consumption (kW h/ha)			Quantity of water (m^3/ha)		Productivity (10^5 kg/ha)	
Crops	Drip irrigation	Surface irrigation	Drip irrigation	Surface irrigation	Drip irrigation	Surface irrigation
Sugarcane	1325	2385	9400	21500	0.14	0.11
Grapes	2483	3959	2780	5320	0.24	0.20
Banana	5913	8347	9700	17600	0.68	0.52

Table 22
Equivalent electrical energy use, water use and productivity of fruit crops in Iran.

Crop	Energy for irrigation (kW h/ha)	Quantity of water (m^3/ha)	Percent of total energy use (%)	Productivity (kg/ha)	Reference
Mandarin	1633	17,470	23	31,500	[179]
Orange	1175	12,570	21	32,500	[179]
Apple	376.8	4,030	9.6	20,774	[180]
Kiwi Fruit	356.4	3,812	12.9	24,547	[181]
Sugar cane	347.1	35,000–45,000	75	93,500	[182]

Table 23
Equivalent electrical energy use, water use and productivity of crops in Turkey.

Crop	Energy for irrigation (kW h/ha)	Quantity of water (m3/ha)	Percent of total energy use	Productivity (kg/ha)	Reference
Pomegranate	370.73	–	10.13	35,119	[186]
Cherry	231.33	4006	10.61	7,156	[184]
Sugar beet	172.66	2990	4.75	60,820	[183]

equivalent electrical energy input to irrigate an agricultural crop in Iran was 0.09 kW h/m^3 [179].

Table 23 reviews energy consumption for irrigating crops from Turkey. It should be noted that surface irrigation was used to irrigate the sugar beet (a root crop) while cherry was irrigated with sprinkler irrigation [183,184]. A combination of surface irrigation and drip irrigation was used for pomegranate. The productivity of the root crop was very high compared to fruits namely cherry and pomegranate while energy consumption was comparatively low. Equivalent electrical energy consumed for agricultural irrigation in Turkey was estimated to be 0.05 kW h for every cubic meter of water [185].

Fruits are found to require energy intensive irrigation when compared to vegetables. This becomes clear from comparison of the energy ranges in Figs. 35 and 36. A common feature that can be seen from both Figs. 35 and 36 is the similar energy use trends with change in location. The energy expenditure for ground water use increased from farms near Sacramento River to those along Tulare Lake. This variation points to a comparatively deep water table in Tulare lake region when compared to farms at San Joaquin, Sacramento-San Joaquin delta, and the Sacramento River [170]. The specific types of vegetables, fruits and nuts grown in California were not reported by Benenson et al. [170].

It can be observed from Tables 22–24 that water consumption for irrigating vegetables was less compared to that for fruits. In USA, spinach yield of 11200 kg/ha consumed equivalent electrical energy of 26.6 kW h/ha for its irrigation [187]. In Table 24, root crop potato was found to consume the maximum amount of energy for irrigation among all vegetable crops. This was due to large quantity of water used to irrigate potato almost 11 times from April to September in 2005–2006 [188].

From Table 24, garlic is seen to be an irrigation energy intensive crop compared to cucumber and tomato grown in greenhouses. Tomato production in Turkey is next only to the largest tomato producers China and USA [185]. Yield of Turkish tomatoes was in the order of 45,360 kg/ha compared to 41,780 kg/ha in the United States [185]. Energy use for irrigating tomato crop using drip and furrow irrigation was reported from 95 tomato farms from South Marmara Region in Turkey [185]. The average energy to irrigate tomatoes in Turkey was approximately, 10 kW h/ha [185]. This was very low compared to energy consumption of tomatoes grown inside greenhouses in Iran. Irrigation of tomato crop grown in a hectare of land in Malaysia consumed 387 kW h of electrical energy [192]. United States tomato crop also consumed the same amount of energy as that of Malaysia for irrigation and yielded 41,780 kg/ha [187].

7.3.2. Grain crops

Corn is one of crops with a very high production density per unit area of cultivated land [18]. Different societies in this world use different methodologies for corn production. Pimental [18] reported that corn in USA was more productive owing to better irrigation and mechanization of agriculture than in India. The equivalent electricity calculations in Table 25 are based on the fact that production of 1 kW h of electricity requires an expenditure of almost 3 kW h of thermal energy [18]. Table 25 provides the direct and indirect energies inputs for corn grown in the United States and India. Pimental [193] reports that only 15% of US corn crop is irrigated while the rest is rain-fed. Agriculture in India is predominantly monsoon rainfall dependent. Therefore, corn grown in India consumed far less fuel or electricity for its irrigation.

Apart from corn, rice and wheat are other major grain crops commonly used across the world. "Boro" rice is grown by farmers in Bangladesh and the paddy grain yield of 5469 kg/ha consumed an average 708.5 kW h of electricity for its irrigation [194]. Similar studies were conducted in Malaysia. Table 26 illustrates the equivalent electrical energy spent for irrigating rice in Malaysia during January to July and also during the rice growing season from August to December in 2003. Najim et al. [192] reported that the paddy crop between January and July required more irrigation due to low rainfall compared to the rainfall intensive time between August and December. From Table 26 it is observed that productivity during January to July was lower than August to December. Therefore, it may be observed that energy expenditure for irrigation can be lowered if the crop is produced within climates suitable for their growth.

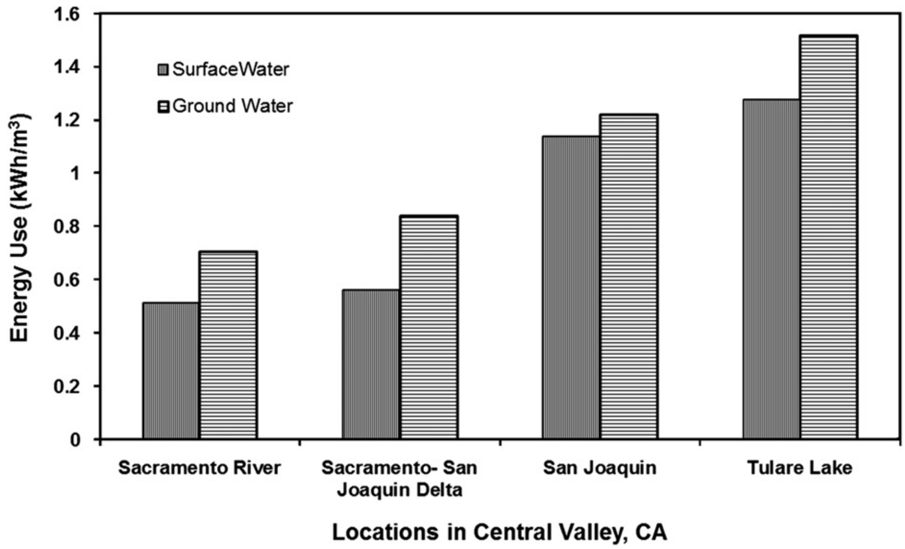

Fig. 35. Energy intensity of sprinkler irrigation for fruits and nuts in Central Valley, CA [170].

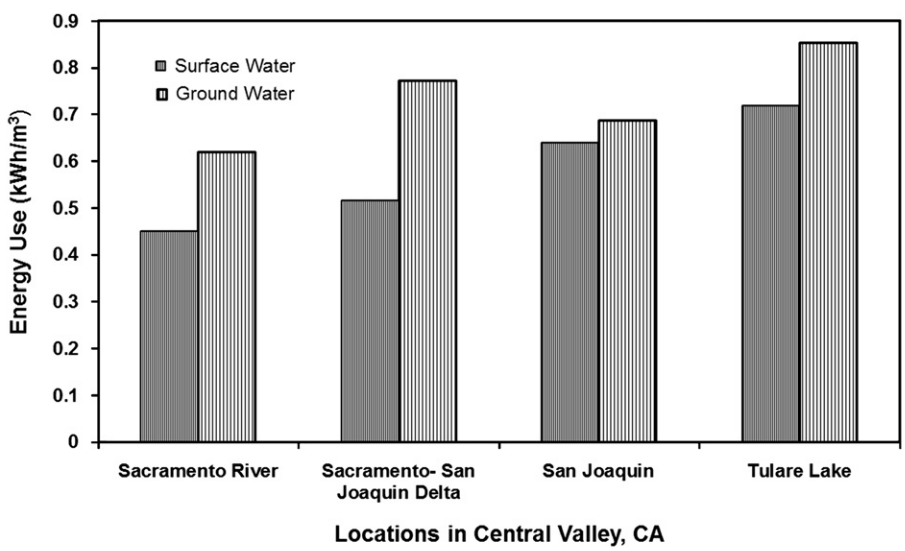

Fig. 36. Energy intensity for sprinkler irrigation of vegetables in Central Valley, CA [170].

Table 24
Equivalent electrical energy use, water use and productivity of vegetable crops in Iran.

Crop	Energy for irrigation (kW h/ha)	Quantity of water (m^3/ha)	Percent of total energy use	Productivity (kg/ha)	Reference
Cucumber (greenhouse)	58.16	622.17	0.43	11,9,762	[189,190]
Tomato (greenhouse)	97.14	Not available	0.81	156,185.6	[190]
Garlic	273.52	2925.9	7.4	16,768.8	[191]
Potato	1042	11145.5	13.93	28,453.6	[188]

From August to December, Malaysian farmers rely on free gravity flow from the central water distribution system owned by government [195]. The energy expenses for irrigation are therefore very much lower. It is also found that energy expended for irrigating rice from August to December in Malaysia was very similar to that consumed in growing 6513 kg/ha rice in California, about 820.34 kW h/ha of electrical energy and 25,000 m^3 of water [187]. This high expenditure of water was not observed in Japan. The rice crop energy consumption in Japan was 349 kW h/ha for producing 6330 kg/ha at a very low water expense of 0.09 m^3/ha [187].

The use of farm machinery influences rice irrigation energy usage. Tractor plowed fields consumed equivalent electrical energy of 1718 kW h/ha for rice production of 4500 kg/ha while bullock plowed fields consumed 2084 kW h/ha for irrigating rice for the same yield [196]. But this trend does not hold in the case of wheat production in India. Tractor plowed fields consumed equivalent electrical energy of 190.7 kW h/ha for wheat production of 2500 kg/ha while bullock plowed fields consumed 167.2 kW h/ha for irrigating wheat for the same yield [196]. This discussion clearly points at the correlation that exists between the direct and indirect energy inputs in agriculture to grow any specific crop.

Table 25
Equivalent electrical energy intensity for corn production in the USA and India [18].

Equivalent electrical energy intensity (kW h/ha)		
Inputs	US corn	Indian corn
Labor	179.07	453.48
Machinery	394.57	71.7
Bullock	0.00	503.87
Diesel	156.98	
Nitrogen	961.24	465.11
Phosphorus	127.13	56.2
Potassium	106.20	
Manure	0.00	372.48
Lime	122.09	
Seeds	201.55	46.89
Irrigation	124.03	
Herbicides	240.31	
Insecticides	108.53	
Electricity	13.18	
Transport	65.50	
Total energy used	3189	1970
Output (kg/ha)		
Corn yield	9400	1721

Table 26
Equivalent electrical energy requirements for rice irrigation in Malaysia [192].

Time	Energy for irrigation (kW h/ha)	Quantity of water (m^3/ha)	Productivity (kg/ha)
January to July	1135	12,620	3230.6
August to December	846.45	11,430	2761.8

Singh et al. [196] studied energy consumption patterns for wheat in India, and their partial findings are reported in Table 27. They reported that due to low rainfall and soils with low carbon content, the State of Rajasthan, India used relatively high energy to irrigate wheat relative to other states in India. Punjab, with the most fertile soils, was the most productive but consumed higher energy for water pumping, since water table levels are decreasing [25]. Indian agriculture has started to adopt drip irrigation recently in the wake of this water scarcity [25]. Wheat farmers from Bhatinda District, Punjab, India used canal based irrigation system to irrigate the wheat crop, which contributed an equivalent electrical expenditure of 125.4 kW h/ha of the total energy expense for irrigation wheat, as illustrated in the Table 26. The energy values reported in Table 27 are very similar to those reported by Pathak and Bining [196] two decades ago. In the USA, irrigation systems used in wheat production consumed 0.001–0.002 kW h of electrical energy for every kilogram of wheat produced [198]. The consumption of energy required to irrigate wheat in Iran was very similar to energy consumption values in India. An average equivalent electrical energy of 374.6 kW h/ha was expended to produce an average yield of 6357 kg/ha of wheat grain utilizing 4147 m^3 of water per hectare [199]. The energy value includes the energy required to pump water on to the wheat fields, which was approximately 228.2 kW h/ha [199].

Sorghum is another grain crop of interest, also known as sweet sorghum due to its application as a sweetener [178]. The productivity for sorghum in the Mediterranean has been studied by several authors [178]. Its yield in desert locations of Tenerife, Canary Islands was 45,000 kg/ha consuming 0.154 m^3 of water per kilogram of dry grain [178]. It is produced in the United States at a comparatively low production rate of 3031 kg/ha, and its irrigation is reported to consume an equivalent electrical energy of 239.7 kW h/ha [187]. In the United States, compared to the rice crop, sorghum consumed less energy for irrigation; but on the other hand more energy than that consumed by wheat.

Table 27
Equivalent electrical energy consumed for irrigating wheat in India [197].

Location in India	District	Timeline	Energy for irrigation (kW h/ha)	Productivity (kg/ha)
Rajasthan				
	Bikaner	1999–2001	160.9	1668.9
	Jodhpur	1999–2001	388.7	2118.3
	Pali	1999–2001	550.26	2133.8
Punjab				
	Nawasahr	1998	374.84	1895
	Hosiarpur	1998	152.15	2952
	Jaisinghwala	1998	277.8	3947
	Sangrur	1998	236	4341
	Bhatinda	1998	147.5	3539
Uttar Pradesh				
	Khamaria and Phulsangi (Tarai)	1998	195.5	2919
	Jaipur Padli and Tejpur Negi (Hill)	1998	81.5	2125
Madhya Pradesh				
	Berkari, Jabalpur	1996–1998	224.5	1241.7
	Sihoda, Jabalpur	1996–1999	328.4	3015.6
	Gwalior	1996–2000	475.26	2857

7.4. Agricultural water treatment

Run-off from agricultural farms is usually treated in wetlands, if at all. Wetlands are natural treatment locations for water polluted with fertilizers, manure, and silt. Wetlands provide a large residence time for impurities to settle. Energy consumption data for such wetlands is not available. The energy intensity for agricultural water reuse using conventional treatment plants in Australia was calculated to be 0.38 kW h/m^3 [36]. Average energy consumption of constructed wetlands in China is 0.25 kW h/m^3 [141].

8. Implications

A detailed picture on energy use is now available for water use in different sectors. We can use this information to return to the water life cycle discussed at the outset and to provide energy values for each block. This cycle can be drawn specifically for particular regions. For example, the water–energy cycle for Australia, California, and Canada are given in Figs. 37–39, respectively. These have been populated with the specific energy intensity data (in kW h_e/m^3 of water) for each of the major processes at each stage of the cycle.

Water supply in Australia is predominantly carried out using ground water and surface water pumping. It is seen the long distance hauling of water in pipelines has increased the energy intensity of surface water pumping when compared to the ground water pumping itself. Desalination processes have increased the upper limit energy consumption values of conventional water treatment. Domestic water heating consumed a major fraction of the overall energy expended for water services and applications in Australia. This is also very true for the Californian example depicted in Fig. 38. A total of 72% of overall electricity consumed in the water life cycle is expended during end use. Surface water pumping in California is also energy intensive due to long distance pumping of water from Northern California and the Colorado River to Southern California. 19% of the overall electricity consumed by the state of California is spent in this water cycle; about 13% is at end use with about 6% for supply,

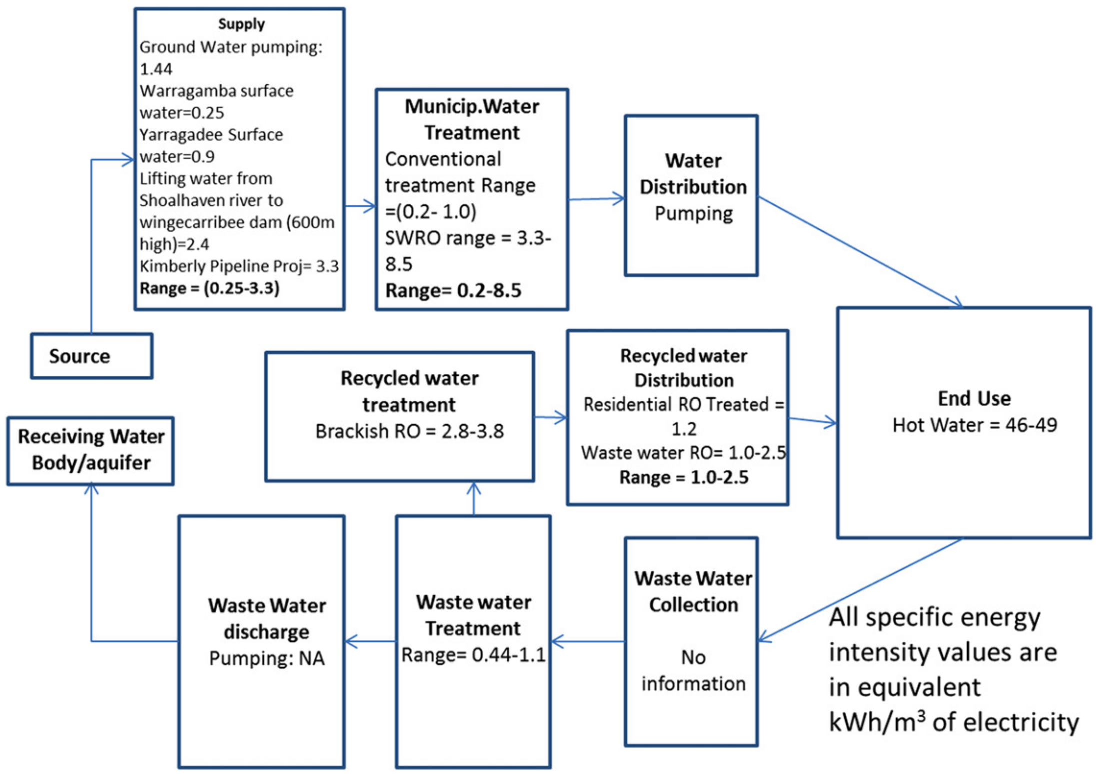

Fig. 37. Stages in the water life through Australian municipal sector showing disaggregating energy use of major processes in each stage, in kW h/m^3 [57,117,140,141,159,200,201].

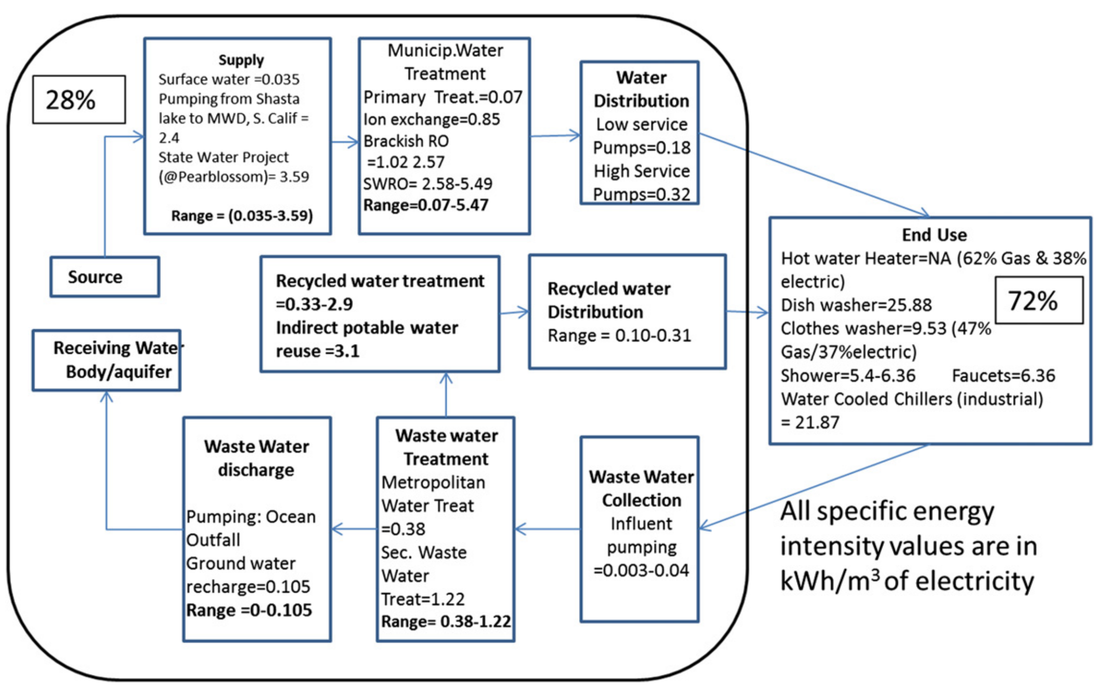

Fig. 38. Stages in the water life through California municipal sector disaggregating energy use of major processes in each stage in kW h/m^3 [65,201]. Approximately 72% of the total energy consumption is at the end use stage [202].

distribution, and treatment [202]. Clearly, reductions in energy intensity and/or water consumption at end use can significantly lower water related energy demand.

It is very clear from Figs. 37–39 that the energy intensity is the highest in the end use component of the life cycle. This is basically due to the fact that water is heated and pumped for occupants or customers using water at end use. It can be seen that the energy consumption for water extraction and supply in Australia is very large as compared to that of Ontario, Canada. Recycling of wastewater is carried out in Australia, and energy intensive reverse osmosis desalination is also widely used in the treatment stage.

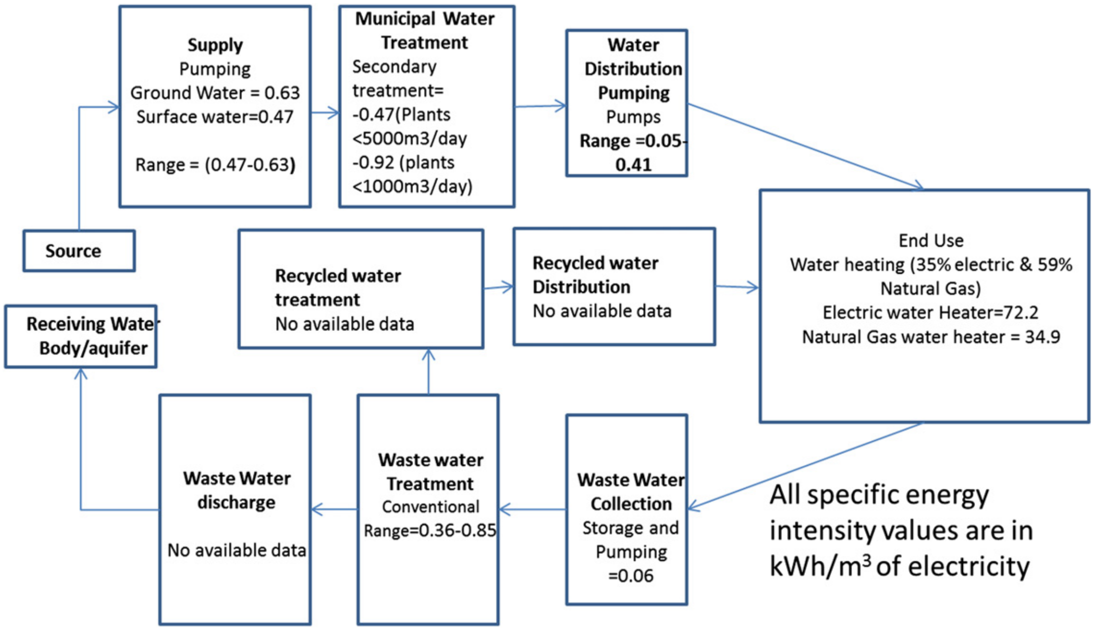

Fig. 39. Stages in the water life through Ontario municipal sector in Canada disaggregating energy use of major processes in each stage in kW h/m^3 [31,32].

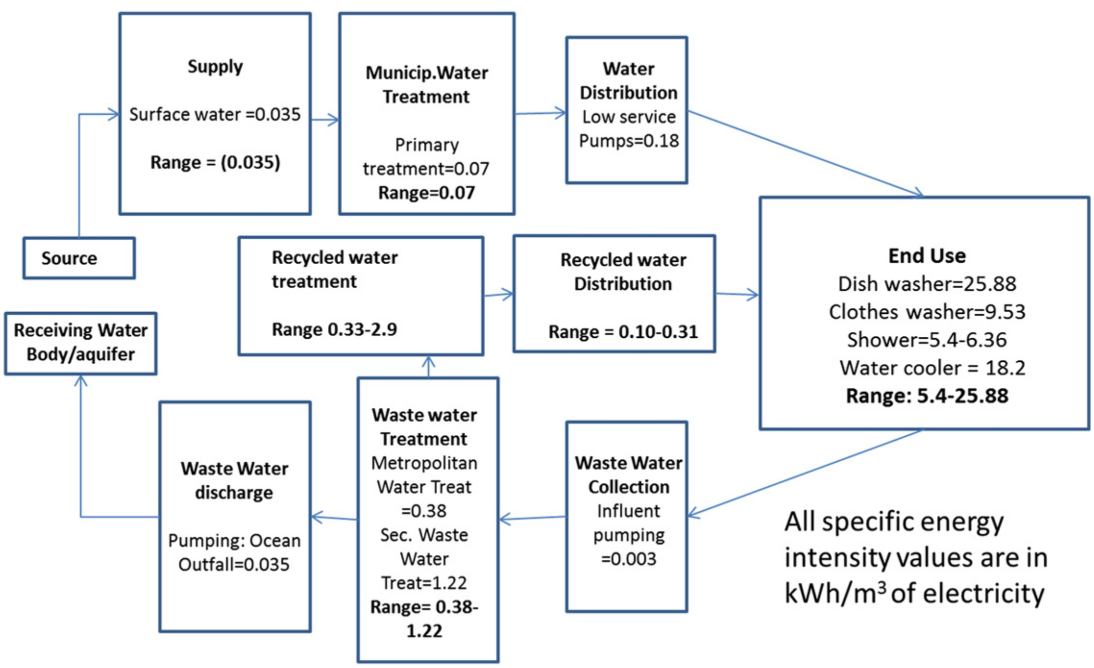

Fig. 40. Low energy consumption scenario for the water supply, treatment, and use life cycle for California in kW h/m^3.

The energy intensities in Fig. 38 are not entirely independent. For example, water scarce Southern California imports water from the Northern California as well as from out of state fresh water sources. The energy intensity of these water transfers (under Supply in Fig. 38) are large and comparable to state-of-the-art desalting [180]. Reverse osmosis (under treatment in Fig. 38) is an alternative to these transfers [203]; and so only one or the other of these two highest intensities would apply to a given delivery of water for end use. Large water transfers also cater to the most water consuming agricultural sector which is predominant in agrarian societies. So in order to better assess the water life cycle it is proposed that an agricultural water use stage also needs to be a part of the water life cycle. Recently a stage of agricultural industry tourism was included in Spain's water use cycle [204].

In order to critically analyze the options for managing energy use in the water life cycle, a low energy use scenario and a high energy use scenario can be outlines as shown in Figs. 40 and 41. In the low energy use scenario, surface water pumping over short distances appears as the lowest energy consumer. It is important to realize that pumping seawater from the Pacific Ocean to California also accounts under surface water pumping, but the subsequent desalting required would consume substantially more energy than treating raw surface water from fresh water bodies if they are nearby. Obviously, nearby fresh water resources may be inadequate if demand exceeds fresh water supply, so this figure should be viewed as an illustration of a low energy consumption baseline.

The low service pumping in Fig. 40 indicates only energy required to meet the pressure demands of water distribution networks. The end use stage of basic daily residential sector

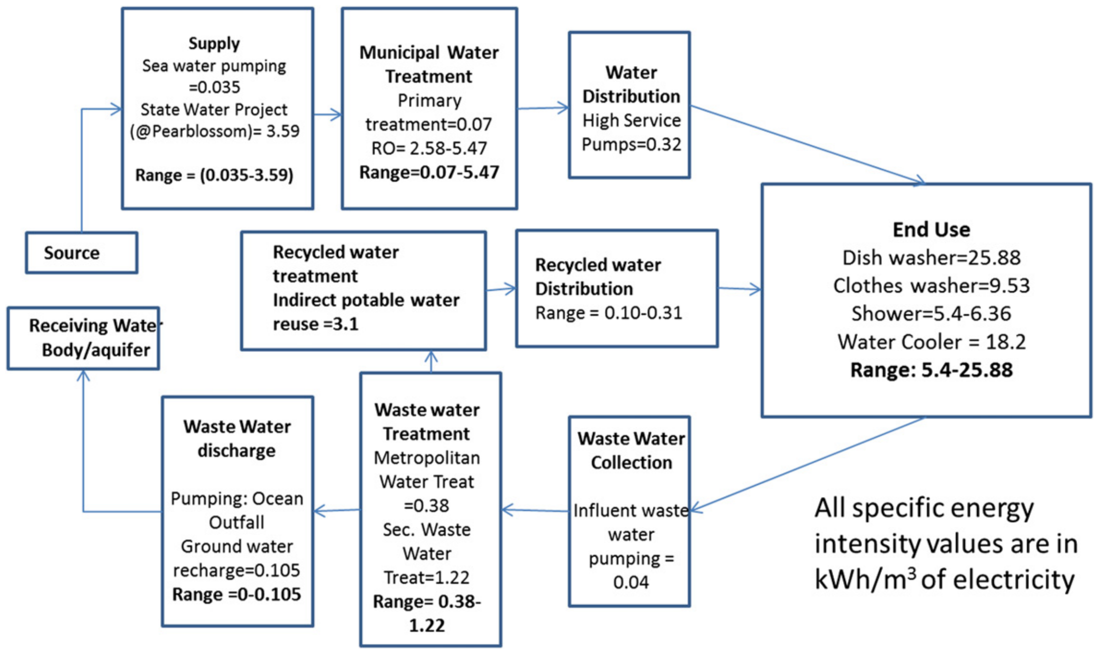

Fig. 41. High energy consumption scenario for the water supply, treatment, and use life cycle for California in kW h/m^3.

requirements is essentially the same for both scenarios in Figs. 40 and 41, in so far as the use of dishwashers, clothes washers, showers, etc., is inevitable in a typical home. However, energy efficient technologies for use in households may present significant opportunities for the reduction of energy consumption at end use, and the potential for energy savings is clearly highest in the end use stage of the water life cycle. Therefore information energy and water use efficiency of technologies (in water life cycle) is an important decisive factor influencing energy consumption.

In the wastewater treatment stage, the quality of the incoming waste water as well as the quality of the waste water discharged back to land or water bodies is taken into consideration. Use of waste water effluents for processes such as landscape irrigation, flushing toilets, thermal power plant cooling, etc. does not require high purity. Therefore, low energy conventional waste water treatment can be proposed as in Fig. 40.

In the high energy use scenario for California, site specific influences are apparent in the framework of Fig. 41. For example, water scarce Southern California imports water from the water abundant north as well as from out of state fresh water sources. The energy cost for water conveyance to Southern California is enormous and comparatively larger than the lower range of energy use for desalting. This can be confirmed from the prior discussions pertaining to energy expenditure incurred for hauling of water by the State Water Project, as also depicted in Fig. 41. Fig. 41 shows that the energy requirements for desalting water from the Pacific Ocean, from brackish water desalination, and from waste water recycling for potable require relatively low energy compared to long distance hauling using aqueducts and pumping stations [202]. Therefore, it appears that the use of local saline water supplies or reuse can reduce the overall energy cost for water in California.

9. Conclusions

Energy consumption for water production, treatment, supply, use and recycling has been reviewed in this article. In the production stage, ground water pumping is usually found to be more energy intensive than surface water pumping, with the exception of situations in which water is hauled extremely long distances to the point of use. Desalination processes are the most energy intensive options in the water treatment stage, and they will only yield energy efficiencies as an alternative to long distance hauling of water. In conventional water treatment systems, pumping processes consume the largest fraction of total energy. Membrane filtration processes are the most energy intensive water disinfection processes. The energy consumption in conveyance and treatment is location specific. Site specific factors are very important in determining the processes used, and thus the energy consumption in each stage of the water cycle differs by location.

From this study, as in previous studies, it is found that end use is the most energy intensive stage in the water–energy cycle. In the residential sector, the energy consumption of heating water increases with demand; hot water energy consumption patterns in the residential sector also vary with climate. Human behavior influences energy consumption as well. Mechanized clothes washers have varied energy performance, and the local cultural practices affect the machine washing technology in the local market. Europe consumed more energy for heating water to wash clothes than Japan. Manual dishwashing was found to be more water and energy intensive than mechanized dish washing machines. Boiling water for cooking was a major consumer of energy in the residential sector. Cooking large quantities of food is by mass less energy intensive than cooking small quantities. The greatest potential for energy savings associated with water consumption lie at the end use component of the water life cycle.

In wastewater treatment plants, digestion is the process that consumes most of the energy in small capacity plants (<4000 m^3). With advanced waste water treatment, which is in growing demand, energy consumption increases. Energy consumption in waste water treatment is linearly related to the size of the population served.

In agriculture, surface as well as ground water is extracted for irrigation. Pressure based pumping systems are found to have high energy intensity. With an increase in pressure requirements at point of use, energy consumption increases. With area, the amount of water used for irrigation increases, and this in turn increases the energy consumed per unit volume of water. The energy intensities in irrigation also change with the type of crops

planted, for example, fruits are more energy intensive than vegetables. The direct and the indirect input energies for crop production are interdependent on each other. Relatively little data is available on energy analysis of waste water treatment systems associated with agricultural water reuse.

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